RESPONDING TO GLOBAL CLIMATE CHANGE

IN CANADA'S ARCTIC

NORTHWEST
TERRITORIES

Environment Canada Environnement Canada

Volume II of the Canada Country Study: Climate Impacts and Adaptation

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RESPONDING TO GLOBAL CLIMATE CHANGE

in

CANADA'S ARCTIC

VOLUME II

of

THE CANADA COUNTRY STUDY: CLIMATE IMPACTS AND ADAPTATION

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Environment Canada Environnement Canada

Canada

This is a component report of the Canada Country Study: Climate Impacts and Adaptation. In addition to a number of summary documents, the first phase of the Canada Country Study will produce six regional volumes, one volume comprising twelve national sectoral reports, and one volume comprising eight cross-cutting issues papers. This is The Canada Country Study - Volume II: Canada's Arctic.

For further information on the Canada Country Study (CCS), please contact the CCS national secretariat in Toronto, Ontario at 416-739-4389 (telephone), 416-739-4297 (fax), or ccs.cia@cciw.ca (e-mail).

Ce rapport est une partie composante de L'Étude pancanadienne sur les impacts et l'adaptation à la variabilité et au changement climatique. En plus de quelques documents sommaires, la première phase de L'Étude pancanadienne produiront six tomes régionaux, un tome comprenant douze rapports nationaux au sujet des secteurs sociaux et économiques, et un tome comprenant huit papiers concernant les questions intersectorielles. Ce rapport est L'Étude pancanadienne - Tome II: Rapport Regional pour l'Arctique canadien.

Pour plusieurs renseignements concernant L'Étude pancanadienne (ÉPC), contactez le secrétariat national de l'ÉPC à Toronto à 416-739-4389 (téléphone), 416-739-4297 (facs.), ou ccs.cia@cciw.ca (poste élect.).

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TABLE OF CONTENTS

List of Figures .iv
List of Tables v
Preface vii
Préface x
Executive Summary .xiv
Résumé .xviii

A. INTRODUCTION 3

B. THE NORTHERN CONTEXT 5
    Background 5
    Ecozones 6
    Socio-Economic Sectors 9

C. CLIMATE OF THE ARCTIC 11
    Climate Controls 11
    Normal Climate 11
    Recent Climate Trends 16
    Scenarios of Climate Change 27

D. ARCTIC IMPACTS AND ADAPTATION 37
    Aspects of the Physical Environment 37
        Hydrology 37
        Permafrost 39
        Sea Ice and Icebergs 41
        Sea Level and Coastal Processes 47
        Freshwater Ice 48
    Terrestrial and Marine Ecological Systems 49
    Socio-Economic Sectors 53
        Oil and Gas 54
        Transportation 56
        Building and Construction 59
        Recreation and Tourism 61
        Settlements, Country Food and Human Health 62
        Agriculture and Forestry 66
        Fisheries 67
        Defence 67

E. OPPORTUNITIES FOR FURTHER RESEARCH 69

REFERENCES 71

LIST OF FIGURES

Figure 1. The Canadian Arctic . . . 4
Figure 2. Arctic Region ecozones . . . 6
Figure 3. Projected economic activity in the mainland Arctic related to non-renewable resources . . . 9
Figure 4. Mean upper-air pattern at 50 kPa for (a) January and (b) July . . . 12
Figure 5. Mean daily surface air temperature for (a) January, (b) April, (c) July and (d) October . . . 14
Figure 6. Mean monthly precipitation for (a) January, (b) April, (c) July and (d) October . . . 17
Figure 7. Mean annual total precipitation . . . 19
Figure 8. Mean annual total rainfall . . . 20
Figure 9. Mean annual total snowfall . . . 21
Figure 10. Canadian climate regions . . . 22
Figure 11. Annual mean temperatures for the three Canadian climate regions in the Arctic . . . 23
Figure 12. Seasonal mean temperatures for the Mackenzie climate region, 1948 to 1997 . . . 24
Figure 13. Seasonal mean temperatures for the Arctic Tundra climate region, 1948 to 1997 . . . 25
Figure 14. Seasonal mean temperatures for the Arctic Mountains and Fjords climate region, 1948 to 1997 . . . 26
Figure 15. Seasonal precipitation departures for the Mackenzie climate region, 1948 to 1997 . . . 28
Figure 16. Seasonal precipitation departures for the Arctic Tundra climate region, 1948 to 1997 . . . 29
Figure 17. Seasonal precipitation departures for the Arctic Mountains and Fjords climate region, 1948 to 1997 . . . 30
Figure 18. Projected change in mean winter (Dec.-Feb.) temperature based on the CCC GCM (1992) for a doubling of atmospheric CO_2 . . . 31
Figure 19. Projected change in mean spring (Mar.-May) temperature based on the CCC GCM (1992) for a doubling of atmospheric CO_2 . . . 32
Figure 20. Projected change in mean summer (Jun.-Aug.) temperature based on the CCC GCM (1992) for a doubling of atmospheric CO_2 . . . 32
Figure 21. Projected change in mean autumn (Sep.-Nov.) temperature based on the CCC GCM (1992) for a doubling of atmospheric CO_2 . . . 33
Figure 22. Projected change in mean winter (Dec.-Feb.) precipitation based on the CCC GCM (1992) for a doubling of atmospheric CO_2 . . . 33
Figure 23. Projected change in mean spring (Mar.-May) precipitation based on the CCC GCM (1992) for a doubling of atmospheric CO_2 . . . 34
Figure 24. Projected change in mean summer (Jun.-Aug.) precipitation based on the CCC GCM (1992) for a doubling of atmospheric CO_2 . . . 34
Figure 25. Projected change in mean autumn (Sep.-Nov.) precipitation based on the CCC GCM (1992) for a doubling of atmospheric CO_2 . . . 35
Figure 26. Derived annual evapotranspiration . . . 38
Figure 27. Permafrost distribution . . . 40
Figure 28. Potential movement of the permafrost boundaries . . . 42
Figure 29. Mean sea-ice concentration for March 26 . . . 43
Figure 30. Mean sea-ice concentration for September 10 . . . 43
Figure 31. Mean date of the complete freeze-over of salt water . . . 45
Figure 32. Mean date of salt water clear of ice . . . 45
Figure 33. Mean maximum ice thickness of undisturbed first-year floes . . . 46
Figure 34. Winter recreation and tourism classification . . . 63
Figure 35. Summer recreation and tourism classification . . . 63

LIST OF TABLES

Table 1. Northwest Territories GDP by industry in 1986 dollars 10
Table 2. Response of permafrost to climate warming 41
Table 3. Oil and gas wells drilled in the Canadian Arctic 54
Table 4. Sensitivity of oil and gas operations to climate 55
Table 5. Climate and related variables affecting Arctic transportation 58
Table 6. Limiting climate factors for recreation and tourism 60
Table 7. Winter recreation-tourism classification 62
Table 8. Summer recreation-tourism classification 62
Table 9. Environmental changes in the Hudson Bay bioregion observed by Cree and Inuit 65
Table 10. Sources of recommendations for impact research on specific socio-economic sectors and aspects of the biophysical environment 70

PREFACE

The Canada Country Study

Intent

The Canada Country Study (CCS): Climate Impacts and Adaptation is a national assessment of the impacts of climate change and variability on Canada as a whole, including consideration of existing and potential adaptive responses. In presenting this national perspective, it draws upon studies of a number of regional, sectoral and cross-cutting issues, of which this volume is one.

The study was initiated by Environment Canada (EC) and is being lead by the Environmental Adaptation Research Group, a component of EC's Atmospheric Environment Service located in Downsview, Ontario. Among the participants are representatives of various levels of government, the university community, the private sector and non-governmental organizations.

In providing Canadians with a balanced, realistic picture of what climate change and variability means for Canada as a whole, the CCS effort builds upon a number of sectoral and regional impact studies that have been completed during the past decade.

The CCS will provide information to Canadian policy makers in the public and private sectors, socio-economic decision makers, the scientific community both domestically and internationally, non-governmental organizations, and the Canadian general public.

Structure

Work on the CCS is divided into two phases. Phase I began in the summer of 1996 and will conclude in the fall of 1997; it is focussed on an extensive review and assessment of all existing literature, the identification of knowledge gaps, and the development of recommendations for future research. The latter would be addressed in Phase II which is expected to begin in late 1997 and extend over approximately a five-year period.

In Phase I, a number of summary reports will be published - a national policy makers summary, a national plain language summary, and six regional plain language summaries. In addition, the basis of these summaries - 26 component studies and papers - are being published in 8 volumes as follows:

Vol. I - British Columbia and Yukon
Vol. II - Arctic
Vol. III - Prairies
Vol. IV - Ontario
Vol. V - Québec
Vol. VI - Atlantic
Vol. VII - Sectoral (comprising 12 national papers on agriculture, built environment, energy, fisheries, forestry, human health, insurance, recreation and tourism, transportation, unmanaged ecosystems, water resources, and wetlands)
Vol. VIII - Cross-Cutting (comprising 8 national papers on changing landscapes, costing, domestic trade and commerce, extra-territorial influences, extreme events, integrated air issues, sustainability, and the two economies).

The Climate Background

Climate Change and Variability

Climate may be thought of as a description of the regularities and extremes in weather for a particular location. It is also, however, naturally variable; from our own experience, we know that one summer is often warmer than another, or one winter is colder or snowier than another. Such variability is a normal feature of a stable climate, and is related to changes in ocean currents or sea-surface temperatures, volcanic eruptions, alterations in the sun's output of energy, or other complex features of the climate system some of which are not yet fully understood.

Natural large-scale climate shifts (or climate changes, such as those that resulted in past ice ages or warm interglacial periods) are driven by long-term alterations in the position of the Earth with respect to the sun. Such alterations can be reflected in changes in the composition of the Earth's atmosphere, an important characteristic of which is the occurrence of certain greenhouse gases (such as carbon dioxide and methane). These gases keep the Earth's surface and atmosphere from cooling too rapidly and help to maintain surface temperatures within the range needed to support life.

Greenhouse gas concentrations have been observed to be lowest during periods of cold climate (ice ages) and highest during warm periods. This connection is of concern because human activities since the beginning of the industrial revolution over 200 years ago (mainly involving the burning of fossil fuels) have greatly increased the concentration of such gases in the atmosphere. Scientists expect to see a doubling of the atmospheric composition of carbon dioxide, for example, within the next century. The increase so far is already considered to have had a discernible effect on the Earth's climate, an effect which is expected to continue.

Models and Scenarios

In order to understand how the world's climate may respond, elaborate supercomputer models of the climate system are used. Known as general circulation models or GCMs, these models are used to simulate the type of climate that might exist if global concentrations of carbon dioxide were twice their pre-industrial levels. Although the models disagree about many of the details of a doubled carbon-dioxide climate, the results of the simulations all agree that the Earth would be warmer, on average (with more warming occurring towards the poles), and would experience overall increases in both evaporation and precipitation. These simulations of climate are referred to as GCM-driven scenarios - distinct from actual forecasts for the future - since they depict a possible future based on certain assumptions about atmospheric composition. The most recent report of the Inter-governmental Panel on Climate Change (IPCC - *qui vive*), issued in 1995, projects an increase in global surface temperature of 1 to 3.5°C over the next 100 years. This may be compared with the observed increase of 0.3 to 0.6°C over the past 100 years.

For its first Phase, the CCS does not follow a single climate scenario. It reflects the range of scenarios that have been used as a basis for the various papers and reports appearing in the scientific literature. In general, the main model scenarios used come from one of five GCMs which have been developed in Canada, the United States, or the United Kingdom.*

While there is an increasing level of comfort with the validity of GCM results at the global scale, such comfort decreases when we look at the regional scale. For Canada there are broad areas of agreement in model results including warming over much of the western and northern areas, but there is also some disagreement between models as to the location and magnitude of areas of surface temperature or precipitation change, particularly in eastern Canada. This disagreement is reflected in the words of uncertainty that appear at times in this volume of the Canada Country Study.

The International Context

International concern about the future of our climate has been building steadily over the past 20 years. One of the first important international conferences to look at the issue was held in Canada in 1988 - The Changing Atmosphere: Implications for Global Security. Also that year, the IPCC was established by the World Meteorological Organization and the United Nations Environment Programme with a mandate to assess the science of climate change, its environmental and socio-economic impacts, and possible response strategies. The IPCC subsequently published formal assessments in 1990 and 1995, with a third to follow in 2000 or 2001.

In 1992, the United Nations Conference on Envi-

***CCC92 - Canadian Centre for Climate Modelling and Analysis 2nd Generation model**
GFDL91 - Geophysical Fluid Dynamics Laboratory model (US)
GISS85 - Goddard Institute for Space Studies model (US)
NCAR93 - National Center for Atmospheric Research model (US)
UKMO95 - UK Meteorological Office model

ronment and Development was held in Rio de Janeiro and resulted in consensus on a Framework Convention on Climate Change (FCCC). This Convention's objective is stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. It has now come into force and involves commitments to actions including emissions reductions, assistance to developing nations, reporting on emissions inventories, scientific and socio-economic research to reduce uncertainties, as well as education and training. Canada's domestic response to the FCCC has been its National Action Plan on Climate Change.

To date, as the objective of the FCCC would suggest, much of the international emphasis on response strategies for dealing with the impacts of climate change has focussed on reducing emissions of greenhouse gases. Respecting that climate change will be with us for a long time, a very important complement to such reductions is the need to understand the impacts of and to adapt to changing climate. The Canada Country Study is one of Canada's responses to recognizing the importance of impacts and adaptation.

Climate Impacts and Adaptation

The major concern arising from the climate change issue is the impact it may have on our environment, our economy, and therefore, on the way we live both now and in the future.

In Canada, we are accustomed to dealing with variations in climate both geographically and seasonally across the country. These variations have many impacts that can reverberate through natural and man-made systems, including water resources, vegetation and wildlife, agricultural practice, forestry and fisheries, energy supply and demand, buildings and roads, recreation and tourism, the insurance industry, and human health.

At present, there are many good examples of our ability to adapt to the range of climate conditions which we both collectively in our economy and as individuals in our everyday life are used to facing. If we depend upon wildlife species for sustenance, we follow them when migratory routes change; we plant different types of crops in different locations at different times of the year; we construct roads and buildings using designs that are compatible with ground that may or may not be characterized by permafrost or with differing snow and wind loads; we build ships and other marine platforms capable of withstanding expected wave heights and sea-ice conditions; we locate recreational facilities and events where they can benefit from appropriate climate conditions, such as sufficient snow for skiing or enough wind for sailing.

When thinking about adaptation as a way to respond to current climate and we then consider an on-going climate change and its impacts, we look for answers to the following questions so that our future planning can be done most effectively:

- What are the impacts of a changing climate and how will they affect me and my family through our lives?
- Are decisions being made today which will increase our vulnerability in the future because they are not taking such impacts into account?
- Will the approaches we use to adapt to the current climate still be workable in the future, or will new approaches be necessary to adapt to changes beyond our historical experience?
- Will the rate of changing climate allow enough time to adapt?
- Should society become more adaptable or flexible to changes in climate than it is now, and if so, how?

The Canada Country Study is aimed at helping to answer some of these questions.

PRÉFACE

L'Étude Pancanadienne

Objet

L'Étude pancanadienne (ÉPC) sur les impacts et l'adaptation à la variabilité et au changement climatiques est une évaluation nationale des impacts du changement et de la variabilité climatiques sur l'ensemble du Canada, qui examine notamment les mesures actuelles et éventuelles d'adaptation. L'élaboration de cette perspective nationale fait appel à des études sur un certain nombre de questions régionales, sectorielles et intersectorielles, dont fait partie ce volume.

Cette étude a été entreprise par Environnement Canada (EC) et est dirigée par le Groupe de recherche en adaptation environnementale, composante du Service de l'environnement atmosphérique d'Environnement Canada, dont les bureaux sont à Downsview (Ontario). Parmi les participants à cette étude figurent des représentants de différents paliers de gouvernement, du milieu universitaire, du secteur privé et d'organisations non gouvernementales.

Afin de fournir aux Canadiens une image juste et réaliste de ce qu'impliquent le changement et la variabilité climatiques pour l'ensemble du Canada, l'ÉPC a fait fond sur un certain nombre d'études d'impact régionales et sectorielles qui ont été réalisées dans la dernière décennie.

L'Étude pancanadienne fournira de l'information aux décideurs canadiens des secteurs public et privé, aux décideurs du domaine socio-économique, à la communauté scientifique nationale comme étrangère, aux organisations non gouvernementales, ainsi qu'à l'ensemble des Canadiens.

Structure

Les travaux de l'ÉPC se divisent en deux étapes. L'étape I a été entreprise à l'été 1996 et prendra fin à l'automne 1997; il s'agissait essentiellement de faire un examen et une évaluation approfondis de la littérature existante, de repérer les lacunes dans les connaissances, et d'élaborer des recommandations pour les recherches à venir. Ce dernier aspect sera l'objet de l'étape II, qui devrait commencer à la fin de 1997 et se prolonger sur environ cinq ans.

L'étape I débouchera sur la publication d'un certain nombre de rapports de synthèse, soit un résumé national à l'intention des décideurs, ainsi qu'un résumé national et six résumés régionaux de vulgarisation. De plus, les rapports généraux sur lesquels sont fondés ces résumés, soit un regroupement de 26 études et documents, seront publiés en huit volumes, comme suit :

- Vol. I - Colombie-Britannique et Yukon
- Vol. II - Arctique
- Vol. III - Prairies
- Vol. IV - Ontario
- Vol. V - Québec
- Vol. VI - Atlantique
- Vol. VII - Questions sectorielles (12 documents nationaux sur l'agriculture, le milieu bâti, l'énergie, les pêches, la foresterie, la santé humaine, les assurances, les loisirs et le tourisme, les transports, les écosystèmes naturels, les ressources en eau et les terres humides).
- Vol. VIII - Questions intersectorielles (8 documents nationaux sur la transformation des paysages, les frais, le commerce intérieur, les influences extraterritoriales, les phénomènes extrêmes, les questions atmosphériques intégrées, la durabilité et les deux économies).

Historique du climat

Changement et variabilité climatiques

On peut considérer le climat comme une description des constantes et des extrêmes des conditions météorologiques d'un endroit donné. Par contre, le climat est naturellement variable. Ainsi, nous en avons l'expérience, il arrive souvent qu'un été soit plus chaud qu'un autre, ou un hiver plus froid ou plus neigeux qu'un autre. Cette variabilité est une caractéristique normale d'un climat stable, et tient aux fluctuations des courants océaniques ou des températures des eaux de surface de la mer, aux éruptions volcaniques, aux modifications de l'émission d'énergie par le Soleil, ou à d'autres caractéristiques complexes du système climatique dont certaines ne sont pas encore parfaitement comprises.

Les variations naturelles à grande échelle du climat (ou les changements climatiques, comme ceux qui se sont traduits par les glaciations et les périodes interglaciaires chaudes du passé) sont le résultat de modifications à long terme de la position de la Terre par rapport au Soleil. Ces modifications peuvent induire des changements dans la composition de l'atmosphère terrestre, dont l'une des caractéristiques importantes est la présence de certains gaz à effet de serre (comme le dioxyde de carbone et le méthane). Ces gaz protègent la surface et l'atmosphère de la Terre contre un refroidissement trop rapide et aident à maintenir les températures de surface dans la plage nécessaire au maintien de la vie.

On a observé que les concentrations de gaz à effet de serre étaient plus basses durant les périodes de climat froid (périodes glaciaires) et plus élevées durant les périodes chaudes. Cette relation est préoccupante car, depuis le début de la révolution industrielle, il y a plus de 200 ans, les activités humaines (surtout la combustion de combustibles fossiles) ont provoqué une forte augmentation de la concentration de ces gaz dans l'atmosphère. Selon les scientifiques, on pourrait assister, dans le prochain siècle, à un doublement de la concentration de dioxyde de carbone dans l'atmosphère. On considère que l'augmentation survenue à ce jour a déjà eu un effet perceptible sur le climat de la Terre, effet qui devrait se poursuivre.

Modèles et scénarios

Pour comprendre comment pourrait réagir le climat mondial, on utilise des modèles complexes du système climatique tournant sur superordinateur. Connus sous l'appellation de « Modèles de circulation générale » ou MCG, ces modèles servent à simuler le type de climat qui pourrait exister si les concentrations planétaires de dioxyde de carbone doublaient par rapport aux niveaux de l'ère préindustrielle. Bien que les modèles divergent sur nombre des détails d'un climat à double CO_2, l'ensemble des simulations confirment que le climat de la Terre serait généralement plus chaud (avec un réchauffement plus marqué près de pôles), et qu'il y aurait une augmentation globale de l'évaporation et des précipitations. Ces simulations du climat, appelées « scénarios issus des MCG », ne sont pas des prévisions comme telles, mais décrivent un futur éventuel fondé sur certaines hypothèses quant à la composition de l'atmosphère. Le plus récent rapport du Groupe d'experts intergouvernemental sur l'évolution du climat (GIEC - cf. infra), publié en 1995, prévoit un réchauffement de la surface du globe variant entre 1 °C et 3,5 °C au cours du prochain siècle; il convient de comparer ces valeurs avec le réchauffement de 0,3 °C à 0,6 °C observé au cours du dernier siècle.

Pour sa première étape, l'Étude pancanadienne sur le climat ne suit pas un scénario climatique unique. Elle prend plutôt en compte toute la gamme de scénarios sur lesquels se sont fondés les spécialistes pour préparer les différents documents et rapports parus dans la littérature scientifique. D'une façon générale, les principaux scénarios utilisés proviennent de l'un des cinq MCG mis au point au Canada, aux États-Unis ou en Angleterre.*

Bien que l'on ait de plus en plus confiance dans la validité des résultats fournis pas les MCG à l'échelle planétaire, cette confiance s'érode lorsque l'on descend à l'échelle régionale. Pour le Canada, on constate de vastes secteurs de concordance entre les résultats des différents modèles, notamment le réchauffement du climat dans une grande partie de l'ouest et du nord; mais il y a également certaines divergences en ce qui concerne la localisation et l'ampleur des transformations qui toucheront les températures de surface et les régimes de précipitations, particulièrement dans l'est du Canada.

*CCC92 - Centre canadien de modélisation et d'analyse climatiques, modèle de 2^e génération.
GFDL91 - Modèle du Geophysical Fluid Dynamics Laboratory (États-Unis)
GISS85 - Modèle du Goddard Institute for Space Studies (États-Unis)
NCAR93 - Modèle du National Center for Atmospheric Research (États-Unis)
UKMO95 - Modèle du Bureau météorologique du Royaume-Uni

L'incertitude exprimée à certains endroits dans le présent volume de l'Étude pancanadienne traduit ce désaccord.

Le contexte international

Au cours des 20 dernières années, l'avenir du climat mondial est devenu une préoccupation de plus en plus constante à l'échelle internationale. L'une des plus importantes conférences internationales sur cette question s'est déroulée au Canada en 1988 et s'intitulait « L'Atmosphère en évolution : implications pour la sécurité du globe ». Cette même année, le GIEC a été créé conjointement par l'Organisation météorologique mondiale et le Programme des Nations Unies pour l'environnement, avec le mandat d'évaluer les données scientifiques disponibles sur l'évolution du climat, les incidences écologiques et socio-économiques de cette dernière, et de formuler des stratégies de parade. Le GIEC a ensuite publié deux rapports d'évaluation en 1990 et 1995, et un troisième devrait suivre en l'an 2000 ou 2001.

En 1992 se tenait à Rio de Janeiro la « Conférence des Nations Unies sur l'environnement et le développement », dont les travaux ont permis d'en arriver à un consensus quant à une Convention-cadre sur les changements climatiques (CCCC). L'objectif ultime de la Convention est de « stabiliser les concentrations de gaz à effet de serre dans l'atmosphère à un niveau empêchant toute perturbation anthropique dangereuse du système climatique ». La Convention est maintenant en vigueur et comporte des engagements relatifs à certaines mesures comme la réduction des émissions, l'aide aux pays en développement, la préparation de rapports sur les inventaires d'émissions, l'exécution de recherches scientifiques et socio-économiques en vue de lever les incertitudes, ainsi que des activités d'information et de formation. En réponse à la CCCC, le Canada a mis au point son propre « Plan national d'action sur le changement climatique ».

À ce jour, conformément à l'objectif de la CCCC, la majorité des efforts déployés à l'échelle internationale pour élaborer les stratégies de parade face aux impacts des changements climatiques ont surtout porté sur la réduction des émissions de gaz à effet de serre. Étant donné que nous devrons composer longtemps avec les changements climatiques, il est important de comprendre leurs incidences et de nous y adapter, en plus d'effectuer ces réductions. L'Étude pancanadienne est l'une des réactions du Canada devant l'importance de ces incidences et de l'adaptation nécessaire.

Climat: impacts et adaptation

Les impacts qu'il peut avoir sur notre environnement, sur notre économie et, par conséquent, sur notre mode de vie actuel et futur sont la principale préoccupation liée au changement climatique.

Au Canada, nous sommes habitués à composer avec les variations de climat qui se manifestent dans tout le pays, aussi bien d'une région à l'autre que d'une saison à l'autre. Ces variations ont de nombreux impacts, qui peuvent se répercuter sur les systèmes naturels et anthropiques, notamment les ressources en eau, la végétation et la faune, les pratiques agricoles, la foresterie et les pêches, la production et la consommation d'énergie, les bâtiments et les routes, les loisirs et le tourisme, l'industrie de l'assurance et la santé humaine.

Il y a déjà nombre de bons exemples de notre capacité d'adaptation à la diversité des conditions climatiques auxquelles nous devons faire face, aussi bien collectivement dans notre économie qu'individuellement dans notre vie quotidienne. Si notre subsistance dépend de la présence d'espèces sauvages, nous les suivons lorsqu'elles modifient leurs voies de migration; nous plantons des types de cultures différents selon les endroits et le moment de l'année; nous construisons les routes et les bâtiments différemment selon que nous sommes ou non sur du pergélisol, ou en fonction de différentes charges de neige et de vent; nous construisons des navires et des plates-formes marines qui peuvent résister aux hauteurs de vagues et aux conditions des glaces de mer prévues; nous aménageons les installations de loisirs et organisons les événements de manière qu'ils bénéficient de conditions climatiques favorables, comme assez de neige pour le ski ou assez de vent pour la voile.

Si l'on considère l'adaptation comme une façon de réagir face au climat actuel, et que l'on examine un changement climatique en cours et ses impacts, on doit répondre aux questions suivantes pour planifier l'avenir le plus efficacement possible :

- Quels sont les impacts du changement climatique, et de quelle façon viendront-ils se répercuter sur ma vie et celle de ma famille?
- Prend-on aujourd'hui des décisions qui viendront accroître notre vulnérabilité future parce qu'elles ne tiennent pas suffisamment compte de ces impacts?
- Les approches que nous utilisons pour nous adapter aux conditions climatiques actuelles seront-elles encore viables dans l'avenir, ou faudra-t-il en envisager de nouvelles pour nous adapter à des changements dépassant tout ce que nous avons connu?
- La vitesse à laquelle se produiront les changements climatiques nous laissera-t-elle le temps de nous adapter?
- Le société devra-t-elle devenir plus adaptable et plus souple qu'elle ne l'est maintenant face aux changements climatiques et, si oui, comment?

L'Étude pancanadienne a pour objectif de nous aider à répondre à certaines de ces questions.

EXECUTIVE SUMMARY

In the Arctic, the Mackenzie District has warmed by 1.5°C over the past 100 years (the warming being most pronounced in winter and spring). The Arctic tundra area has warmed by 0.5°C, but mainly prior to the 1970s. On the other hand, since about 1970, the Arctic mountains and fjords area has cooled slightly, mainly in winter and spring.

Global circulation models (GCMs) suggest increased global annual mean temperature relative to the present of 1 to 3.5°C by 2100 including the possible effects of future changes in atmospheric aerosol content. Pertinent to the circumarctic area are such features as: maximum warming in high northern latitudes in winter, little warming in summer, increased precipitation and soil moisture in high latitudes in winter.

For the Canadian Arctic, winter should see a 5 to 7°C warming over the mainland from west to east and over much of the Arctic Islands, and up to a 10°C warming over central Hudson Bay and the Arctic Ocean northwest of the Islands; summer is likely to see up to a 5°C warming on the mainland extending into the central Arctic Islands, and 1 to 2°C over northern Hudson Bay and the northwestern High Arctic Islands. There is some suggestion that a modest cooling may occur over the extreme eastern Arctic in winter and spring. For precipitation, increases of up to 25% will be spread throughout the year over much of the region, but mainly in summer and autumn. Some early autumn or spring precipitation currently in the form of snow would become rain.

Potential Impacts on the Physical Environment

- At high latitudes such as in Arctic Canada, **glaciers and ice caps** seem likely to change little in overall size. Enhanced melting at lower altitudes in summer would likely be combined with increased accumulation in higher zones.
- A warmer atmosphere and longer thaw period will be conducive to increased **evaporation** in the Canadian Arctic. Over land, evaporative losses will be modified according to changes in vegetative cover. Recent work for the Mackenzie Basin suggests that evapotranspiration will increase for that area.
- **Northward flowing rivers** throughout the mainland are expected to have decreased flows and levels.
- Over half the discontinuous **permafrost** zone would disappear eventually. The boundary between continuous and discontinuous permafrost will shift northward by hundreds of kilometers although the ultimate position and timing are uncertain. The active layer will deepen slowly in the discontinuous zone to perhaps double its current depth. Pronounced thermokarst topography and increased erosional effects on coasts are likely. There will be an increased frequency of occurrence of shallow landslides.
- **Sea ice** occurrence will decline in northern and western areas. A decrease in Northwest Passage winter fast-ice thickness by about 0.5m (although increased snow cover thickness could temper this) and an increase in the ice-free season of 1 to 3 months are expected. The open water season should lengthen from the current average of 60 days to about 150 days for the Beaufort Sea. The maximum extent of open water in summer will increase from its present range of 150-200km to 500-800km; and the maximum thickness of first-year ice will decrease by 50-75%. Decreased first-year ice ridging thickness and old-ice incursion frequency (given no change in wind regime) are also anticipated. There will possibly be increased sea-ice extent in the eastern Arctic area in winter.
- **Iceberg** calving rates would likely change little. Concentrations of icebergs in eastern Arctic waters may therefore remain fairly stable.
- **Sea level** - Overall, much of the Arctic has low sensitivity to such change as its coastline is generally emergent, but the Beaufort Sea area will be highly sensitive, as will some glacial shores on Bylot, Devon, Baffin and Ellesmere Islands.
- **Coastal Processes** - An increase in storm surge frequency will impact some areas significantly, such as the Beaufort Sea. In addition, some coastal areas currently protected virtually year-round from wave action by sea ice (such as the northwest Arctic Islands) will be at risk.

- **Freshwater Ice** - The river ice season will be reduced by up to a month by 2050, and up to 2 weeks for large lakes.

Potential Impacts on Natural Ecosystems

- **Terrestrial vegetation** - Current global Arctic biomes are expected to change in area as follows: ice - shrink by up to ¼, and tundra and taiga/tundra - shrink by up to ⅔ of their present sizes, with the Southern Arctic Ecozone effectively disappearing from the mainland. Ecosystem composition will change (more shrubs and moisture tolerant vegetation, less nonvascular plants) and species diversity will decrease. The speed at which forest species grow, reproduce, and re-establish themselves or that appropriate soils can be developed will be outstripped. Shrinking of the Arctic tundra biome will occur hand-in-hand with a northward shift of the treeline, by up to 750 km in eastern Keewatin. An increase in forest fires, along with more insects and a longer growing season, is expected to result in noticeable changes in vegetation in the Mackenzie Basin. Insects now common to southern Canada would move into the Mackenzie Basin area. Similarly the pests which are in the region today would move not only further north but also to higher elevations. Peatlands will be extremely vulnerable to climate change and would likely switch from a carbon sink to carbon source.
- **Terrestrial Wildlife** - In the Arctic, it is the indirect effects of global warming on feed and water availability that will be the more significant for wildlife. Changes in timing and abundance of forage availability and parasite infestations may accumulate to drive populations into decline with serious consequences for people still depending on them. Mainland caribou would be increasingly stressed and probably lose weight in part due to heavier snow cover, and in part due to an increase in the number of insects harassing them. North of the mainland, High Arctic Peary caribou and muskoxen may become extinct due to foraging difficulty associated with adverse snow conditions. Predator-prey relations are a critical component of life cycles of Arctic species; such relations will shift where snow cover and snow type distributions change. The summer habitat of shorebirds in the Mackenzie Delta probably would not change much; on balance, projected future changes in climate and environmental conditions are more likely to be detrimental than beneficial to geese.
- **Freshwater and Marine** - Lake temperatures would rise but the effect on fish habitats in freshwater is uncertain. Cold water species might be at greater risk as their potential to adapt is not completely known. Arctic char, for example, is one species which could be affected as the northward expansion of southern fish species, such as brook trout, provides competition. Many species in lakes and streams are likely to shift poleward by about 150 km for every 1°C increase in air temperature. The distribution and characteristics of polynyas (ice-free areas, such as the North Water at the northern end of Baffin Island, Hell Gate between Devon and Ellesmere Islands, in Foxe Basin off the coast from Hall Beach, and in Penny Strait) and ice edges that are vital to Arctic marine ecosystems will change. Impacts on mammals such as polar bears, whales and seals, or on seabirds may be both positive and negative, even on the same species. The range and numbers of some Arctic marine mammals, such as beluga and bowhead whales, may increase or at worst hold steady. Ringed and bearded seals, sea lions and walruses require expanses of ice cover for breeding, feeding and other habitat functions and may suffer population decline through pack ice recession. On the other hand, some species (e.g., the sea otter) could benefit by moving into new territories with reduced sea ice. Consequences for polar bears may be especially of concern - prolonging the ice-free period will increase nutritional stress on the Hudson Bay population until they are no longer able to store enough fat to survive. Should the Arctic Ocean become seasonally ice-free for a long period, it is likely that polar bears would become extinct.

Potential Socio-Economic Impacts

- **Oil and Gas** - Even though climate change is generally viewed as easing the environmental conditions under which exploration and development will be carried out, an increased cost for operations in the Canadian Arctic is likely in the short term, due to the conservative nature of the industry.

- **Transportation** - Northward expansion of agricultural, forestry and mining activities would result in the need for expanded air, marine, rail and road coverage and related facilities. **Air:** Float planes would benefit from a longer ice-free season, but there would be a correspondingly shorter season for winter ice strips. **Marine:** The impacts in Arctic areas would likely be significant. Benefits would take the form of longer shipping seasons in all Canadian Arctic areas with the likelihood of easy transit through the Northwest Passage for at least part of the year, deeper drafts in harbours and channels, and the potential for reduced ice strengthening of hulls and/or reduced need for icebreaker support. On the other hand, increased costs would result from design needs to address greater wave heights, possible flooding of coastal facilities in the Beaufort Sea and Hudson Bay, and the generally increased need for navigational aids owing to increased precipitation and storm frequencies and requirements for search and rescue activities. **Freshwater:** The Mackenzie River barge season would increase, perhaps by as much as 40%, but lower water levels would make navigation more difficult. **Land:** Increased permafrost instability will likely lead to increased maintenance costs for existing all-weather roads and rail beds, at least in the short term.
- **Building and Construction** - Increased air temperature will have a number of effects including: reduced power demand for heating, reduced insulation needs, and increased length of the season for construction activities that occur in summer (heavy construction, which may be confined to winter due to the movement of equipment only being possible on frozen, snow-covered ground, would face a shorter season). Affected in various ways will be: northern pipeline design (negative); pile foundations in permafrost (negative although depends on depth of pile); tailings disposal facilities (positive or negative); bridges, pipeline river crossings, dikes and erosion protection structures (negative); open pit mine wall stability (negative).
- **Recreation and Tourism** - Warmer temperatures would be expected to be beneficial for recreation and tourism in the Arctic (with, for example, the likelihood of extended summer activities into September, at least in the southwestern mainland areas). Yet their impact may be counteracted by stronger wind and/or reduced visibility in some areas. For the Mackenzie Basin, sport hunting could be hurt. In Nahanni National Park only minor changes for river recreation such as canoeing and rafting due to changes in the hydrological regime of the area are anticipated. On the other hand, forest fire and ecological changes traceable to climate change could have significant negative impacts there.
- **Settlements, Country Food and Human Health** - Climate change may affect the distribution and quality of animals and other resources on which the northern economy is based. A shorter winter season with increased snowfall may decrease the ability of people to hunt and trap. In addition, traditional knowledge and local adaptations may no longer be applicable enough to rely on. The health of northerners may be affected through dietary dislocations and epidemiological changes.
- **Agriculture** - Opportunities would be presented in the central and upper Mackenzie Valley areas. For example, wheat production could improve although expanded irrigation services would be needed.
- **Forestry** - In the Mackenzie area, average age of tree will decline and the yields from all stands of commercial timber - both softwood and hardwood - will fall by 50%.
- **Fisheries** - Arctic marine: There will be increases in sustainable harvests for most fish populations due to increased ecosystem productivity, as shrinkage of ice cover permits greater nutrient recycling. There is potential for establishing a self-sustaining salmon population in the western Arctic. Northern freshwater: There will be increases in sustainable harvests for most fish species, due to longer warmer growing seasons and relatively small changes in water levels. A potential increase in the diversity of fish species that can be harvested sustainably is likely, due to increases in the diversity of thermal habitats available to support new species expanding their ranges from the south.
- **Defence** - Canada's position that all waters within the Archipelago are under its sovereign control could be more seriously tested due to more easy access. Increased surveillance and other activities such as a greater search and res-

cue capability will be required. A lower probability of extremely cold weather would result in Arctic weather and climate being looked upon by strategists as less of a natural defence in its own right. Military sites such as Alert will face altered costs due to changes in space heating requirement and infrastructure maintenance. Overall, an increased DND role and attendant costs are envisaged.

Adaptation

Human beings, vegetation and wildlife have shown great ingenuity and resourcefulness in adapting to the environmental conditions which characterize the Arctic, but a rapidly changing climate is almost certain to make some existing adaptation strategies obsolete while creating situations that will require new adaptive responses. Adaptation to the impacts of climate change will also have to occur at the same time as northern communities adjust to numerous other social, institutional and economic changes related to land claims settlements and the creation of new territorial structures such as Nunavut. Climate change could alter many aspects of life, both subsistence and wage-related, in Arctic communities, and in the coming years efforts will have to be intensified to understand how these changes will come about and what effects they will have. Insights from traditional ecological knowledge as well as from modern scientific inquiry will play a key part in this process.

Future Directions

Much work is still needed to understand more fully not only the relationship of climate to all aspects of the biophysical environment as well as socio-economic activities, but also the impacts of climate change on them. In addition to these specific research needs which are well-documented in the literature, there are several general concerns which are pertinent to all such sensitivity- and impact-related research for the Arctic.

- Environmental monitoring: Commitment to continued monitoring of atmospheric and oceanographic variables throughout the Arctic is needed.
- Climate scenarios: There is a need for more credible and detailed regional scenarios than currently available from the GCMs.
- Geographic emphasis: The eastern Arctic is much less well-studied in terms of impacts than the other regions of the Arctic.
- Socio-economic sectors: Existing and potential relationships between climate and socio-economic sectors in the Arctic are even less well-understood than those between climate and the biophysical environment.
- Traditional ecological knowledge: TEK should be more effectively utilized, particularly in respect to quantifying terrestrial and aquatic environmental sensitivity to climate.
- Stakeholder involvement: Real partnerships between researchers and users that involve both communities actively in the planning, developing and carrying out of impact-related research for the Arctic are essential.

RÉSUMÉ

Dans l'Arctique, la région du Mackenzie a connu un réchauffement (maximal en hiver et au printemps) de 1,5 °C au cours des 100 dernières années. La zone de toundra s'est réchauffée de 0,5 °C, mais surtout avant les années 70. Par contre, depuis les alentours de 1970, la région des montagnes et des fjords s'est légèrement refroidie, surtout en hiver et au printemps.

Les sorties des modèles de circulation générale (MCG) suggèrent que, d'ici l'an 2100, les températures mondiales moyennes pourraient monter de 1 à 3,5 °C par rapport à l'époque actuelle, compte tenu des effets possibles d'éventuels changements dans la teneur de l'atmosphère en aérosols. Les caractéristiques qui intéressent la région circumarctique sont les suivantes : un réchauffement maximal aux hautes latitudes nordiques pendant l'hiver, un réchauffement faible en été, et une augmentation des précipitations et de l'humidité du sol aux latitudes élevées en hiver.

Dans l'Arctique canadien, l'hiver devrait connaître un réchauffement atteignant 5 à 7 °C d'ouest en est sur le continent et sur la plus grande partie de l'archipel, et jusqu'à 10 °C sur le centre de la baie d'Hudson et l'océan Arctique au nord-ouest des îles. En été, le réchauffement pourrait être de 1 à 2 °C sur le nord de la baie d'Hudson et le nord-ouest des îles du haut-Arctique, et monter à 5 °C sur le continent et jusque dans le centre de l'archipel. Certains indices laissent penser qu'il pourrait y avoir un léger refroidissement sur l'extrême est de l'Arctique en hiver et au printemps. Pour ce qui est des précipitations, on verra, sur la plus grande partie de la région, des augmentations pouvant atteindre 25 % et réparties sur toute l'année, mais surtout en été et à l'automne. Certaines des précipitations de début d'automne et de printemps qui tombent actuellement sous forme de neige seraient remplacées par de la pluie.

Impacts possibles sur le milieu physique

- Aux latitudes élevées, comme dans l'Arctique canadien, la superficie globale des **glaciers** et **calottes glaciaires** ne devrait pas subir de grand changements. L'augmentation de la fonte estivale aux basses altitudes serait probablement compensée par celle de l'accumulation à plus haut niveau.
- Le réchauffement de l'atmosphère et l'allongement de la période de fonte feront monter l'**évaporation** dans l'Arctique canadien. Sur les terres, les pertes par évaporation seront régies par le nouveau couvert végétal. De récents travaux effectués dans le bassin du Mackenzie suggèrent que l'évapotranspiration y augmentera.
- **Les cours d'eau du continent coulant vers le nord** devraient subir une baisse des débits et des niveaux.
- Plus de la moitié de la zone de **pergélisol** discontinu devrait disparaître à terme. Le décalage vers le nord de la limite entre les pergélisols continu et discontinu se chiffrera en centaines de kilomètres, mais on ne sait pas encore où ni quand elle se stabilisera. L'épaisseur de la couche active augmentera lentement dans la zone de pergélisol discontinu, peut-être jusqu'au double de sa valeur actuelle. On aura probablement un relief thermokarstique prononcé et une augmentation des effets d'érosion sur les côtes. Les glissements de terrain de faible épaisseur seront plus fréquents.
- La **glace de mer** sera moins présente dans les régions nord et ouest. On prévoit un amincissement d'environ 0,5 m de la banquise côtière dans le passage du Nord-Ouest (que pourrait cependant tempérer l'épaississement du couvert nival) et un allongement de 1 à 3 mois de la saison libre de glace. La saison d'eau libre, actuellement de 60 jours en moyenne, devrait atteindre environ 150 jours dans la mer de Beaufort. L'extension maximale de l'eau libre en été, présentement de l'ordre de 150 à 200 km, se situera entre 500 et 800 km, et l'épaisseur maximale de la glace de première année baissera de 50 à 75 %. On prévoit également une diminution de l'épaisseur du crêtage de la glace de première année et de la fréquence d'incursion de la vieille glace (dans la mesure où le régime des vents n'est pas modifié). Il pourrait y avoir une augmentation de l'extension maximale de la glace dans l'est de l'Arctique en hiver.

- Les taux de vêlage d'**icebergs** ne devraient pas changer beaucoup. Les concentrations d'icebergs dans les eaux de l'est de l'Arctique devraient donc rester assez stables.
- **Niveau de la mer** - Dans l'ensemble, la plus grande partie de l'Arctique est peu sensible à ces changements, puisque son trait de côte est généralement en émersion, mais la région de la mer de Beaufort y sera très vulnérable, ainsi que certains rivages glaciaires des îles Bylot, Devon, Baffin et Ellesmere.
- **Processus côtiers** - Un accroissement de la fréquence des ondes de tempête aura une incidence marquée sur certaines régions, comme la mer de Beaufort. En outre, certaines zones côtières que la glace de mer protège actuellement presque toute l'année contre l'action des vagues (comme les îles arctiques du nord-ouest) risqueront d'y être exposées.
- **Glace d'eau douce** - D'ici 2050, la saison des glaces sur les cours d'eau sera plus courte, jusqu'à un mois de moins, et deux semaines pour les lacs de grande superficie.

Impacts possibles sur les écosystèmes naturels

- **Végétation terrestre** - On prévoit que la superficie des grands biomes arctiques actuels changera comme suit : pour la glace, une réduction vers 25%; pour la taïga/toundra, une réduction vers 67% (au Canada, l'écozone arctique du sud serait essentiellement confinée aux îles de l'Arctique). La composition des écosystèmes sera modifiée (il y aura plus d'arbustes et de végétation tolérant l'humidité, et moins de plantes non vasculaires) et la diversité des espèces augmentera. L'échelle de temps de ce changement sera plus courte que la période dont ont besoin les essences forestières pour se développer, se reproduire et se réinstaller, et les sols propices pour s'établir. Le rétrécissement du biome de la toundra arctique accompagnera le décalage vers le nord de la ligne des arbres, qui pourra remonter de 750 km dans l'est de Keewatin. Une augmentation du nombre de feux de forêt et de la présence d'insectes et un allongement de la saison de croissance devraient induire des changements profonds de la végétation dans le bassin du Mackenzie, que gagneront des insectes fréquentant présentement le sud du Canada. De même, les ravageurs qui y sont actuellement présents migreront non seulement vers le nord, mais aussi en altitude. Les tourbières seront extrêmement vulnérables au changement climatique.
- **Faune terrestre** - Dans l'Arctique, ce sont les effets indirects du réchauffement planétaire sur la disponibilité de la nourriture et de l'eau qui toucheront le plus la faune. Si le fourrage n'est plus disponible aux mêmes moments et dans les mêmes quantités, et que les infestations de parasites subissent le même genre de modification, il pourra s'ensuivre un déclin des populations animales, situation qui affecterait gravement les populations humaines qui en dépendent encore. Les caribous de Bathurst qui vivent au nord du Grand lac des Esclaves seraient probablement plus maigres, en partie à cause de l'épaississement du couvert nival, en partie à cause d'une augmentation de la nuisance causée par les insectes piqueurs. Au nord du continent, les populations de caribou de Peary et de boeuf musqué du haut-Arctique pourraient s'éteindre. Les relations prédateur-proie, élément critique des cycles biologiques des espèces arctiques, seront modifiées aux endroits où les distributions du couvert nival et du type de neige changeront. L'habitat d'été des oiseaux de rivage du delta du Mackenzie ne changera probablement pas beaucoup; dans l'ensemble, les changements prévus des conditions climatiques et environnementales devraient être plus néfastes que bénéfiques pour les oies.
- **Eaux douces et de mer** - Les températures des lacs monteraient, mais l'effet de cette situation sur les habitats des poissons dulcicoles reste incertain. Les espèces d'eau froide pourraient être plus menacées, car on ne connaît pas complètement leur potentiel d'adaptation. L'omble chevalier, par exemple, pourrait être affecté par la compétition qu'entraînerait le décalage vers le nord d'espèces méridionales, comme l'omble de fontaine. De nombreuses espèces des lacs et cours d'eau vont probablement migrer vers le pôle d'environ 150 km par degré Celsius d'élévation de la température de l'air. On verra un changement de la distribution et des caractéristiques des polynies (zones libres de glace, comme l'Eau du Nord, à la pointe nord de l'île de Baffin, le Hell Gate entre les îles Devon et Ellesmere, dans le bassin Foxe au large de Hall Beach,

et dans le détroit de Penny) et des lisières des glaces qui sont vitales aux écosystèmes marins de l'Arctique. Les incidences de cette situation sur les mammifères, comme les ours blancs, les baleines et les phoques, ou sur les oiseaux de mer peuvent être à la fois positives et négatives, même au sein d'une même espèce. L'aire de répartition et les effectifs de certains mammifères marins de l'Arctique, comme le béluga et la baleine boréale, peuvent augmenter ou, dans le pire des cas, rester tels quels. Le phoque annelé, le phoque barbu, le lion de mer et le morse ont besoin de grandes étendues de glace pour se reproduire, se nourrir, etc.; un rétrécissement de la banquise pourrait donc entraîner une baisse de leurs populations. Par ailleurs, certaines espèces (comme la loutre de mer) peuvent être avantagées si elles gagnent de nouveaux territoires comportant moins de glace de mer. Pour les ours blancs, les conséquences peuvent être graves; un allongement de la saison sans glace peut accroître le stress nutritionnel sur la population de la baie d'Hudson, jusqu'au point où les individus ne pourraient plus stocker assez de graisse pour survivre. Si la saison sans glace de l'océan Arctique était longue, il est probable que les ours blancs s'éteindraient.

Impacts possibles sur les conditions socio-économiques

- **Pétrole et gaz** - Bien que l'on considère généralement que le changement climatique améliorera les conditions environnementales dans lesquelles sont menées les activités d'exploration et d'exploitation, les opérations dans l'Arctique seront probablement plus coûteuses, vu la nature conservatrice de l'industrie.
- **Transports** - Si les activités agricoles, forestières et minières s'étendent vers le nord, il faudra accroître les réseaux de transport aérien, maritime, ferroviaire et routier, ainsi que les installations connexes. **Transport aérien :** Les hydravions bénéficieraient d'une plus longue saison sans glace, mais la saison des pistes de glace serait d'autant raccourcie. **Transport maritime :** Les impacts sur l'Arctique seraient probablement significatifs. Parmi les avantages figurent l'allongement de la saison de navigation dans tous les secteurs de l'Arctique canadien, avec la probabilité d'une circulation plus facile par le passage du Nord-Ouest au moins une partie de l'année, l'accroissement de la profondeur d'eau dans les ports et chenaux et la possibilité d'avoir moins besoin de renforcer les coques et de faire appel aux services de brise-glace. Par contre, il y aurait une hausse de coûts liée à la conception de navires pouvant affronter des vagues plus hautes, à l'ennoyage possible d'installations côtières dans la mer de Beaufort et la baie d'Hudson, et au besoin généralement plus grand d'aides à la navigation du fait des fréquences accrues de précipitations et de tempêtes, et d'activités de recherche et sauvetage. **Transport en eau douce :** L'allongement de la saison de navigation des barges sur le Mackenzie pourrait atteindre 40 %, mais la baisse des niveaux d'eau rendrait leur circulation plus difficile. **Transport terrestre :** L'instabilité accrue du pergélisol ferait probablement monter les coûts d'entretien de toutes les actuelles plates-formes de routes et de voies ferrées, au moins à court terme.
- **Travaux de construction et d'aménagement** - L'élévation de la température de l'air aura certains effets, dont : une réduction de la demande en énergie pour le chauffage, une baisse des besoins en isolation et un allongement de la saison des activités estivales de construction et d'aménagement (cependant, la réalisation des grands travaux, qui peut être limitée à l'hiver car l'équipement ne peut circuler que sur un sol gelé couvert de neige, ne disposerait que d'une saison plus courte). L'influence se ferait sentir sur : la conception du pipeline du Nord (négative); les fondations sur pieux dans le pergélisol (négative, mais fonction de la longueur des pieux); les installations d'élimination des stériles (positive ou négative); les ponts, les franchissements de cours d'eau des pipelines, les digues et ouvrages de protection contre l'érosion (négative); la stabilité des parois des mines à ciel ouvert (négative).
- **Tourisme et loisirs** - Des températures plus élevées devraient aider le secteur du tourisme et des loisirs dans l'Arctique (avec, par exemple, une extension des activités estivales jusqu'en septembre, du moins dans le sud-ouest de la partie continentale). Cet avantage risque cependant d'être compromis par le renforcement des vents et/ou la baisse de la visibilité en certains endroits.

Dans le bassin du Mackenzie, la chasse sportive pourrait souffrir. Dans le parc national Nahanni, les changements de l'hydrologie de la région n'induiraient que quelques changements mineurs des loisirs aquatiques, comme les descentes en canoé et en radeau. Par contre, les feux de forêt et les modifications de l'écologie découlant du changement climatique pourraient y avoir de graves incidences négatives.

- **Établissements humains, aliments traditionnels et santé de la population** - Le changement climatique peut influer sur la répartition des espèces animales et autres ressources sur lesquelles est basée l'économie du Nord. En outre, les connaissances traditionnelles et les adaptations locales peuvent ne plus être de mise, et donc devenir moins fiables. La santé des populations nordiques pourrait être affectée par les perturbations de l'alimentation et les changements épidémiologiques.
- **Agriculture** - Certaines occasions pourraient se présenter dans les tronçons moyen et supérieur de la vallée du Mackenzie. Par exemple, la production de blé pourrait s'améliorer, mais il faudrait étendre les services d'irrigation.
- **Foresterie** - Dans la région du Mackenzie, l'âge moyen des arbres baissera et le rendement de tous les peuplements de bois commercial - feuillus comme résineux - chutera de 50 %.
- **Pêches** - Eaux marines de l'Arctique: On constatera une augmentation des rendements durables de la plupart des populations de poissons, liée à un accroissement de la productivité des écosystèmes, parce que le rétrécissement du couvert glaciel permettra un meilleur recyclage des nutriants. Il y a un potential d'établir des saumons dans l'ouest de l'Arctique. Eaux douces du Nord: On verra une augmentation des rendements durables de la plupart des espèces de poissons, liée à un allongement et un réchauffement de la saison de croissance et à des changements relativement mineurs des niveaux d'eau. La diversité des espèces de poissons qui se prêteront à une exploitation durable devrait s'accroître, car il y aura une plus grande diversité d'habitats thermiques pouvant accueillir les espèces méridionales qui étendront leur aire de répartition.
- **Défense** - Un accès plus facile pourrait battre en brèche la position du Canada selon laquelle toutes les eaux de l'archipel sont sous sa juridiction souveraine. Il faudra donc accroître les activités de surveillance et autres, comme une meilleure capacité de recherche et sauvetage. Comme il y aura une moindre probabilité d'extrêmes de froid, les stratèges considéreront moins le climat et les conditions météorologiques de l'Arctique comme des remparts naturels. Les coûts de sites militaires comme Alert pourraient changer, en raison des nouveaux besoins en chauffage et en maintenance de l'infrastructure. Dans l'ensemble, on peut s'attendre à ce que le MDN doive jouer un plus grand rôle, avec les coûts que cela entraîne.

Adaptation

L'homme, la végétation et la faune ont eu recours à toutes sortes de stratégies pour s'adapter aux conditions environnementales typiques de l'Arctique, mais l'évolution rapide du climat va très certainement en rendre certaines désuètes, car la situation exigera de nouvelles réponses. Les collectivités du Nord devront s'ajuster aux impacts du changement climatique en même temps qu'à de nombreux autres changements sociaux, institutionnels et économiques. Le changement climatique pourrait influer sur de nombreux aspects de leur vie et, dans les années à venir, il faudra s'attacher encore plus à comprendre comment surviendront ces changements et quels effets ils auront. Les éclairages apportés par les connaissances écologiques traditionnelles et par les recherches scientifiques modernes joueront un rôle clé dans cette démarche.

Orientations futures

Il faudra encore déployer beaucoup d'efforts pour comprendre plus à fond non seulement la relation entre le climat et tous les aspects de l'environnement biophysique et des activités socio-économiques, mais aussi les incidences du changement climatique sur ces facteurs. Outre ces besoins de recherches spécifiques qui sont bien formulés dans la littérature scientifique, il s'est dessiné plusieurs grandes préoccupations concernant toutes les recherches liées à la sensibilité et aux impacts dans l'Arctique.

- Surveillance de l'environnement : Un engagement à poursuivre la surveillance des variables atmosphériques et océanographiques dans tout l'Arctique s'impose.

- Scénarios de climats : On devra disposer de scénarios régionaux plus crédibles et plus détaillés que ceux qu'offrent actuellement les MCG.
- Géographie : L'est de l'Arctique a été beaucoup moins étudié que les autres parties de cette région.
- Secteurs socio-économiques : Les relations actuelles et possibles entre le climat et les secteurs socio-économiques de l'Arctique sont encore moins bien comprises que les liens entre le climat et l'environnement biophysique.
- Connaissances écologiques traditionnelles : Elles devraient être utilisées de façon plus efficace, surtout pour quantifier la sensibilité au climat des milieux terrestre et aquatique.
- Implication des intervenants : Il est urgent que soient noués des partenariats réels entre les chercheurs et les utilisateurs dans le but de développer et d'effectuer les recherches liées aux impacts dans l'Arctique.

RESPONDING TO GLOBAL CLIMATE CHANGE

in

CANADA'S ARCTIC

A. INTRODUCTION

The Arctic Region, here taken to encompass the Northwest Territories, is the subject of this Volume II of the first phase of the Canada Country Study (CCS). Yukon, which is not included, is considered together with British Columbia in Volume I of the CCS. Figure 1 is a map of the region showing the locations of the various districts, settlements, physiological features, islands, and water bodies referred to in the following pages.

This volume describes our current understanding of the impacts that climate change and variability will have on all aspects of the Arctic's physical and biological environment and its socio-economic activities, and of existing or potential adaptation options. In order to do so, it synthesizes a broad range of knowledge drawn from the existing literature, both published and unpublished.

While it is recognized that there are many, complex relationships between the various aspects of the environment themselves as well as between them and socio-economic activities in the region, each aspect and activity is dealt with separately for completeness. Inevitably, this has lead to some overlap in the material presented; however, this was considered preferable to possibly omitting something through taking a more integrative approach.

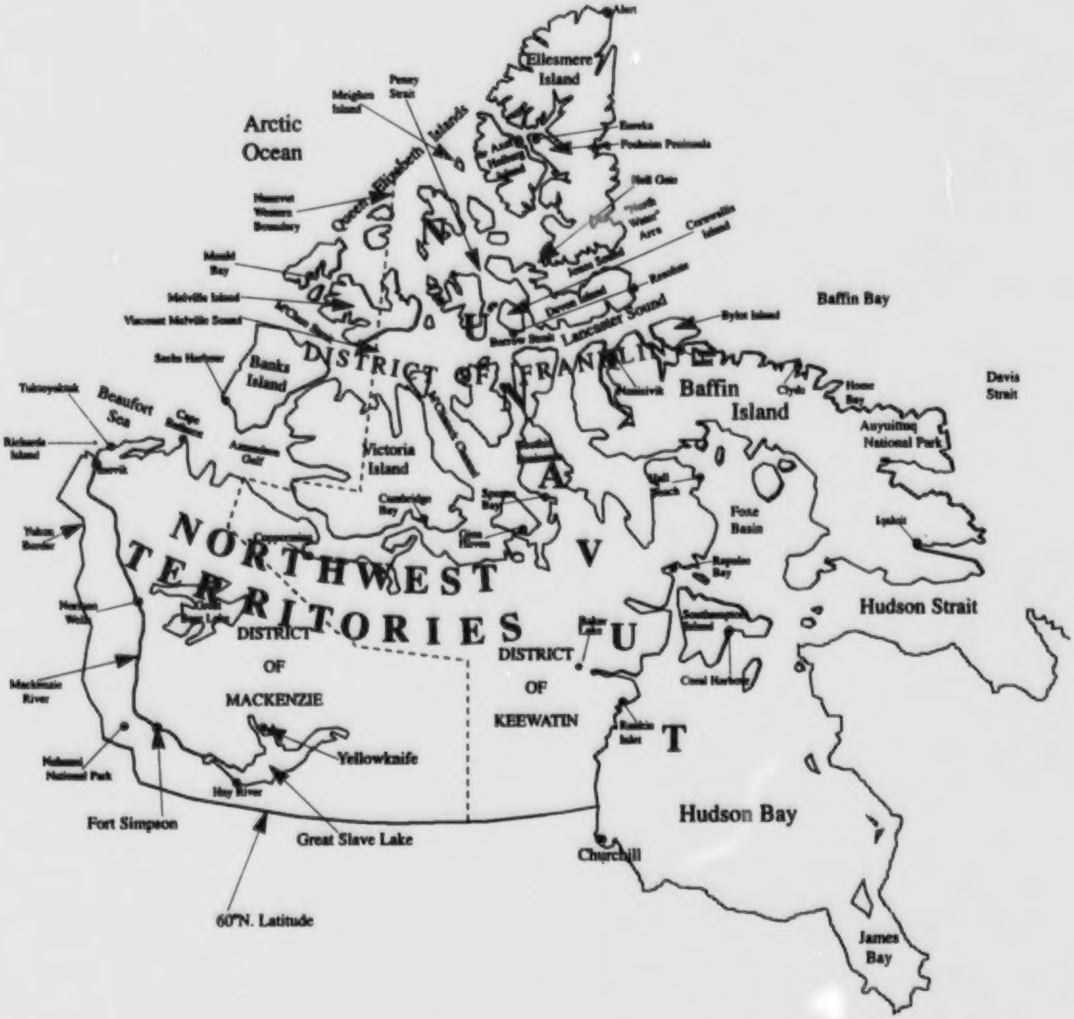

Alert
Ellesmere Island
Penny Strait
Meighen Island
Queen Elizabeth Islands
Arctic Ocean
Eureka
Posheim Peninsula
Axel Heiberg Island
Nunavut Western Boundary
Hell Gate
"North Water" Area
Cornwallis Island
Jones Sound
Mould Bay
Resolute
Devon Island
Melville Island
Viscount Melville Sound
Barrow Strait
Lancaster Sound
Bylot Island
Baffin Bay
Sachs Harbour
Banks Island
DISTRICT OF FRANKLIN
Nanisivik
Baffin Island
Clyde
Home Bay
Davis Strait
Tuktoyaktuk
Beaufort Sea
Cape Bathurst
Richards Island
Inuvik
Amundsen Gulf
Victoria Island
Auyuittuq National Park
Hall Beach
Foxe Basin
Cambridge Bay
Spence Bay
Gjoa Haven
Iqaluit
Yukon Border
NORTHWEST TERRITORIES
Coppermine
NUNAVUT
Repulse Bay
Norman Wells
Great Bear Lake
Southampton Island
Hudson Strait
DISTRICT OF MACKENZIE
Baker Lake
DISTRICT OF KEEWATIN
Coral Harbour
Mackenzie River
Rankin Inlet
Yellowknife
Nahanni National Park
Hay River
Hudson Bay
Fort Simpson
Great Slave Lake
Churchill
60°N. Latitude
James Bay

Figure 1. The Canadian Arctic

B. THE NORTHERN CONTEXT

Much of the material in this section has been extracted from draft Environment Canada documents and is reproduced courtesy of Coleman (1997).

Background

That part of Canada east of Yukon and stretching northward from the 60th parallel to the North Pole is at present known as the Northwest Territories (NWT). As a consequence, however, of the *Nunavut Act* passed by Parliament in June 1993, the NWT will be divided into two separate territories on or before April 1999, with Nunavut in the east, and an (as yet) unnamed territory in the western NWT. Pending that change, the current NWT with an approximately 3.3 million square kilometre area encompasses almost 40% of Canada's land mass, and fronts on approximately two-thirds of Canada's marine coastline.

The Arctic is sparsely populated. The total population was estimated to be 63,900 in 1996 (about 0.2% of the Canadian population). Of these, approximately 39,500 reside in the western NWT and 24,400 in Nunavut, living in widely scattered communities. Over the past forty years, the population has grown at an annual rate of 4.6% - twice the national average. About 25% of the NWT population lives in Yellowknife. Over three-quarters of the 63 communities have less than 1,000 residents. Of the total population, aboriginal persons make up 46 percent in the western NWT and 85 percent in Nunavut. The Canadian average is 3.8 percent. Dene (Indian), Metis, Inuvialuit and Inuit people form the aboriginal population.

The Arctic population is young, with 50 percent under 25 years of age, compared to the Canadian average of 35 percent. According to the 1991 Census, 62 percent of the population of Canada as a whole have completed high school and/or received some post-secondary training. The comparative figure for the NWT is 54 percent. The educational level for aboriginal people is far below these averages, however - only 33 percent in the NWT.

There is a strong contrast in the state of development among communities throughout the North. In the NWT there are quite diverse regional differences in the economy. The eastern Arctic has more small, traditional communities and is generally less developed than the Mackenzie Valley region. Distances between centres and to markets are vast, resulting in high transportation costs. The few developed communities have large populations, large public sector components, relatively good transportation links (including to the south), high per-capita incomes, relatively lower unemployment, and a dominant wage economy. The many traditional communities, with primarily aboriginal inhabitants, tend to have smaller populations, poorer transportation linkages, higher unemployment, significant social problems, higher population growth rates, limited private sector opportunities, and a greater reliance on non-wage economic activities, primarily harvesting of renewable resources.

Aboriginal people (and many non-aboriginal northern residents) have a close affinity to the natural environment. Despite the growth of wage-labour opportunities, hunting, fishing, and trapping have persisted and retain their social, cultural and economic significance. In 1985, country foods had a replacement value of approximately $55 million in the NWT alone (Ames, 1989). As a consequence of this dependence upon the environment, issues affecting that environment often command much higher priority than elsewhere in Canada. Significantly, the NWT was the first jurisdiction in Canada to pass an Environmental Bill of Rights for its citizens.

The political and constitutional development of the Arctic may be attributed, in large part, to the activism of northern aboriginal people. As a result of land claims, the NWT will be divided before the end of the decade and government will be much more accountable to claim beneficiaries. Aboriginal people now have a significant role in the management of northern environmental issues.

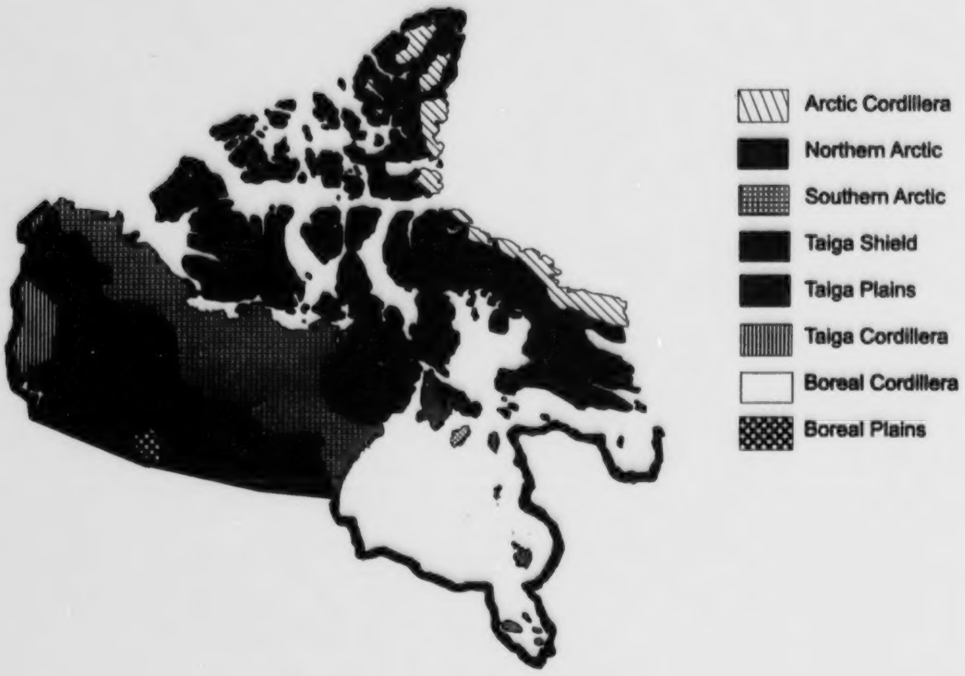


Figure 2. Arctic Region Ecozones.

Despite its relative isolation and sparse population, the Arctic is not insignificant in a national context. In large part, the Arctic defines the Canadian national and international character. Canada is recognized for its northern landscapes - large open spaces, abundant wildlife, and pristine waters. The clients for Canada's northern programs are not limited to northern residents. A large portion of the southern Canadian public (and an international audience) closely monitor northern developments. The Canadian Arctic Resources Committee, for example, is a public-interest group that is solely devoted to the rational development and management of the North.

Ecozones

The Canadian North encompasses a wide variety of ecological zones (Figure 2), each with unique features and relationships. The following is a brief description of the main ecozones which are fully or partially within the Arctic Region in the context of the Canada Country Study.

Taiga Shield Ecozone

The Taiga Shield ecozone stretches across part of Canada's subarctic north. The Russian term 'taiga' refers to the northern edge of the boreal coniferous forest. This is the Athabaskan 'land of little sticks' that stretches from Labrador to Alaska and from Siberia to Scandinavia. In northern Canada, much of this forest rests on the Canadian Shield, the bedrock heart of the continent. With an area of over 1.3 million square kilometres, the Taiga Shield is one of Canada's largest ecozones. One third of it lies in the Northwest Territories.

The unique history of this area includes an unrivaled showcase of bald Precambrian bedrock that dates back to the planet's earliest days. Dotting the ancient landscape are many lakes and wetlands carved by successive waves of glacial erosion and deposition. The Taiga Shield is an ecological crossroads where climate, soils, plants, birds, and mammals from two worlds - the Boreal and the Arctic - meet.

In the Northwest Territories, the settlement of this ecozone began over 7,000 years ago as the Palaeo-Indians followed Barren-ground caribou northwards in the wake of receding glaciers. More recently, this area has played a major role in the story of Canada's development due to its pivotal role in the fur trade, its concentration of rich mineral resources, and its position as a cultural and political focal point for today's aboriginal peoples.

Taiga Plains Ecozone

The Taiga Plains ecozone is an area of low-lying valleys and plains centred on Canada's largest river, the Mackenzie, and its many tributaries. With an area of about 550,000 square kilometres, it is Canada's sixth largest ecozone. Approximately 90% of the Taiga Plains is located in the western Northwest Territories, with small extensions into northeastern British Columbia and northern Alberta. It is bounded to the east by two huge lakes (Great Bear and Great Slave), to the west by the rolling foothills of the Mackenzie Mountains, to the north by the Mackenzie Delta, and to the south by the spruce forest of the Boreal Plains.

The northern reaches of this ecozone feature a rich diversity of plants, birds, and mammals from both the Subarctic and the Arctic. The southern portion is home to the world's largest Wood Bison herd, contains the only known nesting site of the endangered Whooping Crane, and encompasses a wildlife habitat of global significance.

Settlement of the Taiga Plains began around 11,000 years ago, near the end of the last ice age. At that time, the Palaeo-Indian people began moving through an ice-free corridor that stretched down the Mackenzie Valley to the Peace-Athabaska area of western Alberta. Over the past 300 years, the area has played a major role in the northern fur trade, development of frontier oil and gas resources, and provision of a major water transportation route through northwestern Canada. The central importance of large subarctic rivers in the ecology and traditional culture of this area is reflected in a Dene creation story about how the Mackenzie River was born.

Taiga Cordillera Ecozone

The Taiga Cordillera ecozone is a land of magnificent beauty. It is a mountain stronghold of towering peaks, untamed rivers slicing their way between sheer rock walls, broad windswept uplands dominated by alpine and Arctic shrubs and flowers, plus vast wetlands and spruce-lined valleys that support many kinds of wildlife. This land hosts some of Canada's largest waterfalls, deepest canyons, and wildest rivers.

Straddling the Yukon-Northwest Territories border, this ecozone contains the northernmost arc of the Rocky Mountain chain. To the northwest are expansive wetlands and rolling hills that stretch to the Beaufort coast. Treeless Arctic tundra dominates its northern reaches and gives way to a mix of alpine tundra and lowland forests farther south. 'Cordillera' refers to the series of mountain ranges and valleys that form this ecozone's rugged interior. Here the mark of forces that create and destroy mountains can be clearly seen in the record of the rocks.

The diverse habitats from valley bottoms to mountain tops support a wide range of mammals, including two species of both caribou and bears. The birds that nest here include a mixture of species typical of the Arctic and Subarctic, as well as eastern and western Canada.

The earliest human inhabitants of this area migrated across the Bering land bridge during the decline of the last ice age about 12,000 years ago. The ice-free corridor paralleling the Mackenzie Mountains allowed early colonization by the Athabaskan ancestors of today's Slavey, Mountain Dene, and Gwich'in peoples. Industrial developments related to this area's rich oil, gas, and mineral reserves are few, and the northwestern rim of the country remains a vast wilderness area.

Southern Arctic Ecozone

When the first European visitors confronted Canada's Arctic, they called it the Barrenlands. Forming the southern fringe of this massive ecosystem, the Southern Arctic ecozone may indeed seem barren when viewed from a distance. This is a place where nature's abundance and diversity are subdued by the harsh climate and terrain. A closer look at this landscape during the sudden greening of spring or the brief blush of fall, however, will reveal a land of plenty.

For almost a million square kilometres, the pattern of habitats in the Southern Arctic is the same - sprawling shrublands, wet sedge meadows, and cold, clear lakes. Superimposed on this pattern are the fascinating shapes and textures created by intense frost action in the soil. Eskers (ridges of glacially deposited gravel and sand) are prominent topographic features in this landscape.

The Northwest Territories portion of the Southern Arctic ecozone is home to the world's largest concentration of free-roaming large mammals. These are Barren-ground caribou, the so-called 'Buffalo of the Tundra'. They began their annual migration cycle through this area after the last ice age ended. Evidence of that age is still plainly visible in the glacial etchings and deposits found throughout the region.

For thousands of years, the abundant large mammals lured hunters from both sides of the treeline. The Dene and Inuit used its great rivers - the Thelon, Back and Coppermine - to reach caribou, muskox, and moose. They came most often in the fall to secure the large supplies of meat necessary to carry them through the winter. Though floatplanes are now the main mode of access, the rivers are still used by people from all walks of life to enjoy the beauty and bounty of the frontier.

Northern Arctic Ecozone

Covering 1.5 million square kilometres or about one-seventh of Canada, the Northern Arctic ecozone extends over most of the non-mountainous areas of the Arctic Islands and parts of northeastern Keewatin, western Baffin Island, and northern Québec. It is among the largest Arctic ecosystems in the world. Winters pass in near darkness with the polar night measured in weeks and months rather than hours. Snow may fall any month of the year and usually remains on the ground for at least 10 of them, from September to June. Extremely low temperatures and average precipitation of about 200 mm per year characterize the climate. When not covered in snow, much of the landscape is typified by barren plains covered in frost-patterned soils and the occasional rock outcrop.

A desolate, cold and dry land seemingly devoid of life - such might be a visitor's first impression. But to those who have seen the colourful profusion of wildflowers along an Arctic stream, heard the tinkling call of the ascending Horned Lark, or watched a herd of muskoxen stand resolute against a fierce winter blizzard, this land is alive and full of wonder. Peary caribou, found only on the High Arctic Islands, make seasonal movements between the Islands.

Ancestors of modern-day Inuit first inhabited this region more than 5,000 years ago. The climate was warmer in those days, allowing wider settlement of the area than exists today. In adapting to the harsh ecosystem, the original inhabitants developed an intimate connection with the land.

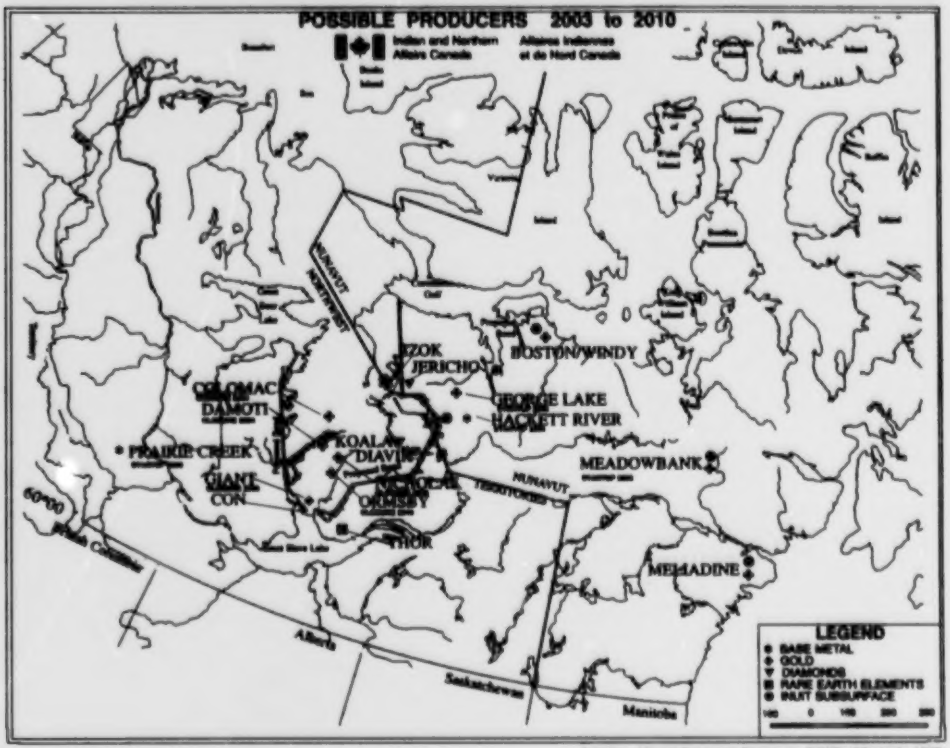
Arctic Cordillera Ecozone

Ice and rock reign supreme in the Arctic Cordillera ecozone, an area featuring some of the world's most spectacular mountain glacial scenery. Massive ice caps and tongued glaciers mask many of the rugged mountains. Some of Canada's highest but least-known peaks are found here, towering over gaping U-shaped valleys and deep fjords that extend many kilometres inland.

The vast mountain chain forms the spine of this ecozone. It runs along the northeastern fringe of the Northwest Territories and Labrador, dominating eastern Baffin and Devon Islands, and most of Ellesmere and Bylot Islands. Due to the extreme cold, high winds, and lack of soil, the higher portions of this ecozone are largely devoid of plants and animals. Ice barrens and frost-shattered rock prevail over much of this landscape.

At lower elevations, pockets of tundra meadow dotted with Arctic flowers and ground-hugging shrubs occupy sheltered valleys, streambanks, and coastlines. During the brief Arctic summer, these sites are oases of concentrated life.

In contrast to the biological impoverishment of


POSSIBLE PRODUCERS 2003 to 2010
Indian and Northern Affairs Canada
Affaires indiennes et du Nord Canada
NUNAVUT
NORTHWEST
IZOK
JERICHO
BOSTON/WINDY
GEORGE LAKE
HACKETT RIVER
COLOMAC
DAMOTI
PRAIRIE CREEK
KOALA
DIAVIK
GIANT
CON
ORMSBY
THOR
MEADOWBANK
MELIADINE
NUNAVUT
TERRITORIES
60°00
Alberta
Saskatchewan
Manitoba
LEGEND
BASE METAL
GOLD
DIAMONDS
RARE EARTH ELEMENTS
INUIT SUBSURFACE

Courtesy: Mineral Resources Directorate, DIAND, Yellowknife, NWT

Figure 3. Projected economic activity in the mainland Arctic related to non-renewable resources.

the land, the adjacent fjords and nearshore waters are richly endowed with marine life. Complex current systems, localized upwellings of nutrients, and polynyas (which remain ice-free year-round) together create the Arctic's most productive aquatic ecosystems. Among the animals living here are globally significant populations of polar bear, narwhal whale, and the endangered bowhead whale.

Although elements of the last ice age persist in the Arctic Cordillera ecozone, the region is a land of surprising vitality. Even the ice itself can come alive to the eyes and ears of patient observers.

Socio-Economic Sectors

The Gross Domestic Product (GDP) of the Northwest Territories was $1,648 million in 1996 (at 1986 prices). Table 1 shows the breakdown of the GDP by industry during the 1990s.

The business sector is now accounting for almost three-quarters of the GDP, with the non-business government sector declining at the territorial and federal levels. The most important business sectors from a GDP standpoint are non-renewables, construction and finance. (Figure 3 shows the projected distribution of mainland non-renewable industry activity early in the next century, based on current exploration activity.) Some sectors such as fishing and trapping and perhaps logging and forestry have a degree of importance as a way of life or a focus for community existence which is much greater than their contribution to the GDP alone would indicate.

Table 1. Northwest Territories GDP by industry in 1986 dollars (in millions of $)

	1996	1994	1992	1990
All industries	1,648.4	1,603.5	1,532.8	1,551.1
Business Sector	1,204.8	1,141.9	1,063.1	1,102.0
Agriculture & Related Services	1.5	1.3	1.2	1.1
Fishing & Trapping	2.5	1.9	3.6	4.7
Logging & Forestry	0.9	0.8	0.6	0.2
Mining, Quarrying & Oil Well	333.8	328.5	308.2	321.5
Manufacturing	7.0	12.8	12.1	16.9
Construction	172.0	152.5	146.3	169.9
Other Utilities	47.5	45.9	42.0	47.3
Transportation & Storage	86.0	80.2	73.8	84.0
Communication	97.6	91.0	89.4	78.9
Wholesale Trade	27.0	28.9	18.6	21.6
Retail Trade	63.2	60.3	55.6	55.8
Finance, Insurance & Real Estate	220.7	209.2	199.3	183.1
Community, Business & Personal	145.0	128.5	112.4	117.2
Non-Business Sector	443.6	461.6	469.7	449.0
Government Service	290.4	311.1	330.2	316.7
Defence	4.2	5.4	6.3	7.3
Federal	86.8	97.7	102.5	109.0
Territorial	149.8	159.5	175.8	158.7
Local	49.5	48.6	45.6	41.6
Community & Personal Services	132.5	128.2	119.8	114.6
Education	74.9	75.3	72.5	72.7
Health & Social Service	48.3	43.8	38.5	33.6
Other Services	9.3	9.1	8.8	8.3
Other Non-Business Sector	20.7	22.3	19.7	17.8
Goods Producing	565.2	543.7	514.0	561.5
Service Producing	1,083.1	1,059.7	1,018.9	989.5

Source: NWT Bureau of Statistics

C. CLIMATE OF THE ARCTIC

The material in this section is drawn from Thompson (1970), Burns (1973, 1974), and Maxwell (1980, 1982, 1986, 1992, 1994, 1997), unless indicated otherwise.

Climate Controls

Much of the Arctic Region is characterized by continuous darkness during several of the winter months and continuous daylight in the summer, although these extremes are tempered in several ways. Complete darkness does not settle in until at least one month after the sun sets completely in the autumn, creating a prolonged Arctic twilight. Even during the polar night, moonlight reflected from snow and ice surfaces noticeably lightens the darkness. In summer, because the days are so long, the total input of solar energy is approximately the same as at lower latitudes, but because Arctic surfaces are highly reflective, a smaller percentage of the available energy actually remains to heat the earth's surface and the atmosphere.

Unequal solar heating of the globe, combined with the earth's rotation, drives general atmospheric circulation, which in turn directs large-scale storm movements. Regional circulation patterns are altered by mountain ranges and by differential solar heating from season to season over different surfaces such as forest, tundra, snow, ice, and water. Atmospheric circulation in the Arctic is dominated by a deep, cold, low-pressure area known as the circumpolar vortex, which extends through the middle and upper troposphere and lower stratosphere. The feature appears on the January 50-kPa mean height pattern as a pronounced area of low heights extending over the North Pole. This area has three distinct troughs, the most intense of which is centred over eastern Canada near northern Baffin Island (Figure 4a). The result is weather systems which are steered from northwest to southeast across Canada in winter. In summer (Figure 4b), the vortex is less intense, with its deepest value occurring over the Pole and no longer solely identified with the eastern Canada trough. With the eastern Canadian trough withdrawn northward, weather systems can then penetrate the Canadian Archipelago routinely.

An important climate control in the Arctic is the nature of the underlying surface. The Arctic Basin is an ice-covered ocean that plays an important role in determining the characteristics of large-scale Arctic air masses, but the seas and channels separating the adjacent islands and land masses exert a dominant influence on the coasts and adjoining lands. For example, spring arrives considerably later in the Arctic than in more temperate areas. This phenomenon is due, first, to the melting of snow and ice, which requires considerable thermal energy and, second, to the high reflective properties of those surfaces. Snow and ice fields also affect the character and movement of low- and high-pressure areas and frontal systems. During summer and autumn, the climate is influenced by the stretches of cold, open water that develop. Thus, local onshore and offshore winds, low clouds, and fog occur frequently in summer, as do snow squalls in autumn.

High land masses can also affect climate. In the eastern Canadian Arctic, for example, the mountain ranges of Ellesmere, Devon, and Baffin Islands, together with Greenland, act as a barrier to mild, moist air that might otherwise penetrate from the North Atlantic. The windward slopes also receive considerably more precipitation than adjacent inland areas, particularly on southeastern Baffin Island. In all other sections of the Arctic, where the rolling hills and plains are generally below 500 m in elevation, the relief is locally important as far as winds and temperature are concerned, but it has little effect on the regional climate.

Normal Climate

Due to the great latitudinal and longitudinal extent of the Arctic, it is difficult to generalize about the length and timing of seasons. The concept of four 3-month seasons (winter, spring, summer, autumn) so familiar to residents of more southerly latitudes of Canada, however, cannot be readily applied to the Arctic's climate. For example, some of the Arctic's coldest weather can occur in late March and April, a time associated with the beginning of spring at the vernal equinox. If spring is considered to start with

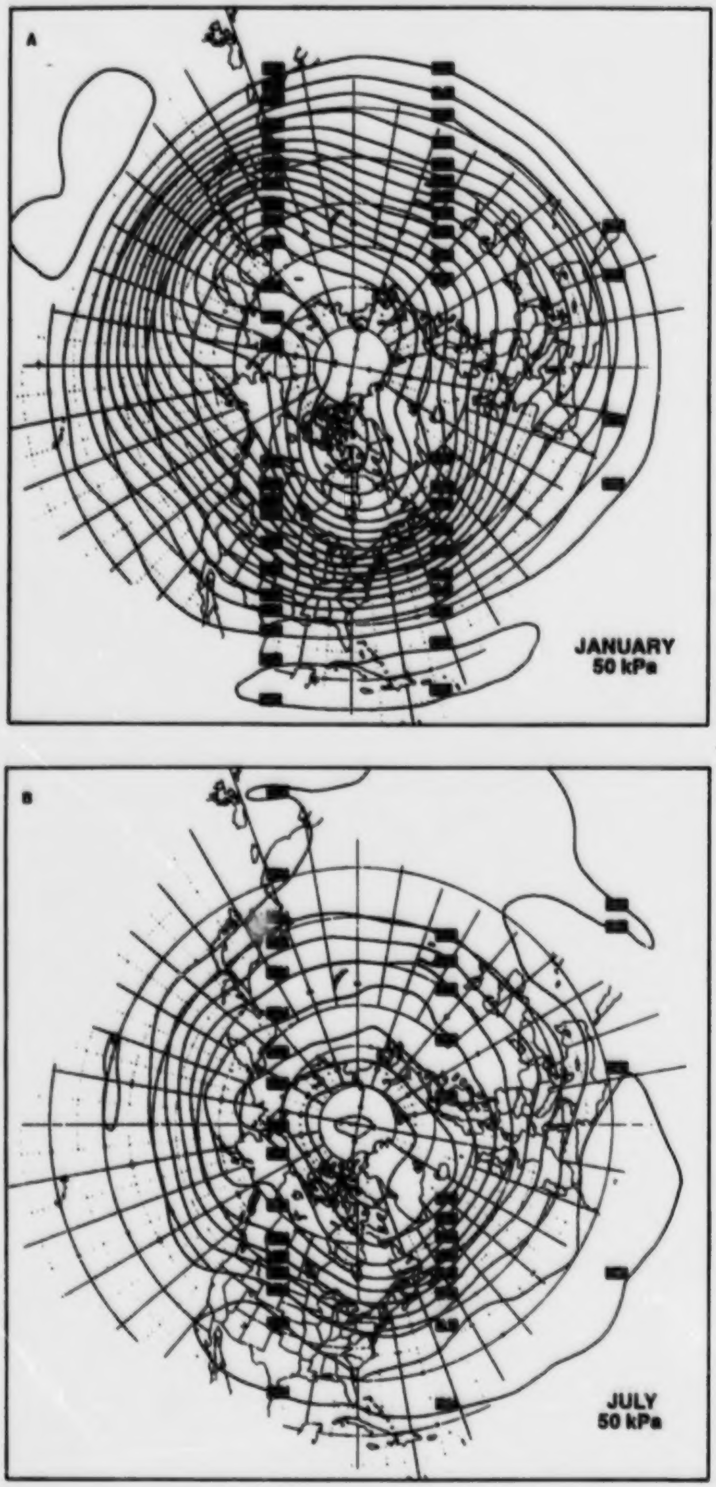

A
JANUARY
50 kPa
B
JULY
50 kPa

Figure 4. Mean upper-air pattern at 50 kPa for (a) January and (b) July (from Maxwell, 1992)

the beginning of the thaw season, then in the Arctic, spring does not begin until late May or early June. Similarly, winter would be considered as beginning in mid-to-late September with the onset of below-freezing temperatures.

In the following paragraphs, the Arctic's climate is briefly discussed based on the year being divided into four periods of roughly uniform conditions. Information on temperature, precipitation, air pressure, and wind conditions is provided and the discussion is supported by Figures 5 through 9.

Late November to early May

By December, the High Arctic is a region of darkness; the southern islands receive only a few hours of twilight at most; and even in the Hudson Bay and mainland areas, four or five hours of mid-day sun do little to replenish the heat lost during long hours of darkness. Bays, channels, rivers and lakes are mostly ice-covered, no longer supplying moisture to the air as they had done during the preceding four or five months.

Surface air temperatures are well below -20°C during December to March, and for the islands north of the Parry Channel, during April as well. Over the mainland, January is the coldest month, but at high Arctic locations, February is most severe with March a close second. On a monthly or annual basis, the Arctic regions are the coldest in Canada; however, due to the moderating effect of surrounding water (even though ice-covered), the extremes in the High Arctic are not as severe as more continental locations elsewhere in Canada. For example, Snag (Yukon) which boasts the lowest recorded temperature in Canada has a mean January temperature 3 to 4°C warmer than that at Resolute or Baker Lake.

The surface pressure pattern for January shows strong low pressure centred over the Baffin Bay area and high pressure over the Mackenzie District in the west. This results in predominantly northwesterly winds (40 to 75% of the time) over much of the region. Local topography, however, has a strong influence on winds so that there are often considerable differences between sites only several kilometres apart.

Of great significance in the Arctic is the occurrence of strong wind in combination with other climate elements. Wind and cold temperatures result in high wind chill, the most severe conditions occurring in the barrens northwest of Hudson Bay. Even light winds combined with the fine, powdery Arctic snow can result in hazardous blowing snow conditions. When the wind is part of a large-scale circulation pattern, such conditions with visibilities reduced to a few metres may cover large areas for periods of three or four days.

The cold Arctic atmosphere contains little moisture at this time of year so that the few disturbances that affect the central portion of the region produce only thin, diffuse clouds and consequently very light snowfall (~10 cm in January). Cloudiness is considerably greater in the southeastern areas near Hudson and Davis Straits and somewhat greater in the southwest, along the Mackenzie Valley. Snowfall in the former area is significant particularly over the mountainous areas of eastern Baffin Island (~70 cm), as mentioned previously; in the latter area, snowfall is somewhat higher (~20-25 cm) than in the barrens to the east and north of the mainland.

Steam fog or Arctic sea smoke (formed when very cold air passes over open water) is often observed in the Arctic during the winter. It forms downwind of open leads or polynyas that may develop either randomly or regularly in ice-covered areas. Usually, it is fairly localized and does not extend more than a few kilometres from the source.

May to June

By May, the Arctic is experiencing continuous or close-to-continuous daylight. Although temperatures are climbing, above-freezing values are not reached until late May or early June. Even at those dates, sharp falls in temperature to near -20°C are possible. In June, temperatures are usually a few degrees above freezing. This, assisted by the almost continuous daylight, results in the accumulated snow of the past season quickly disappearing from most lowland areas. Warmest conditions occur in the southern Mackenzie District with June mean temperatures of 10 to 15°C.

This is a time of increasing cloudiness and snow-

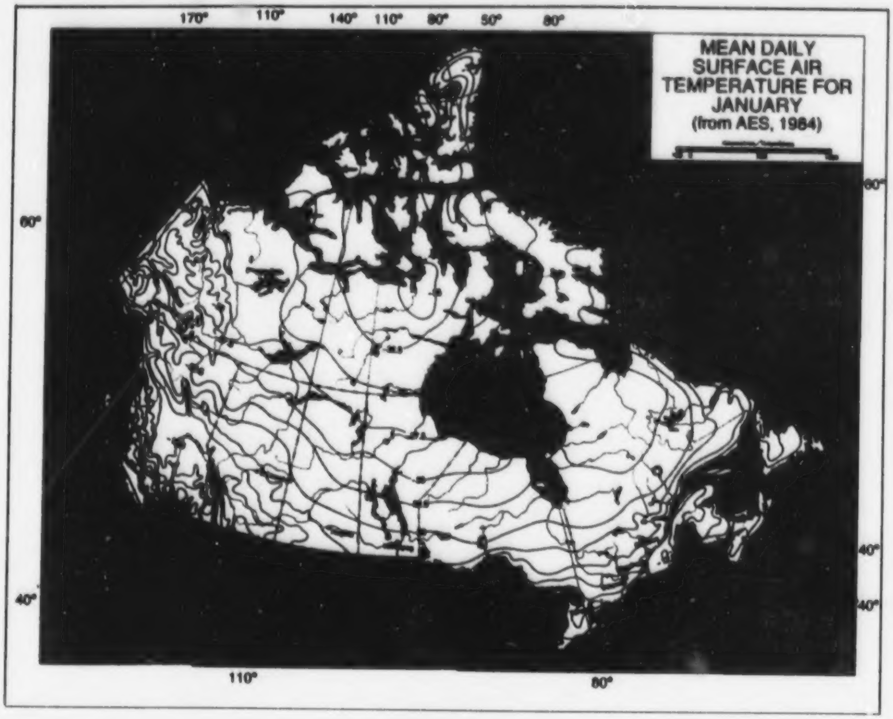

170°
110°
140°
110°
80°
50°
80°
MEAN DAILY
SURFACE AIR
TEMPERATURE FOR
JANUARY
(from AES, 1984)
60°
60°
40°
40°
40°
110°
80°

Figure 5a.

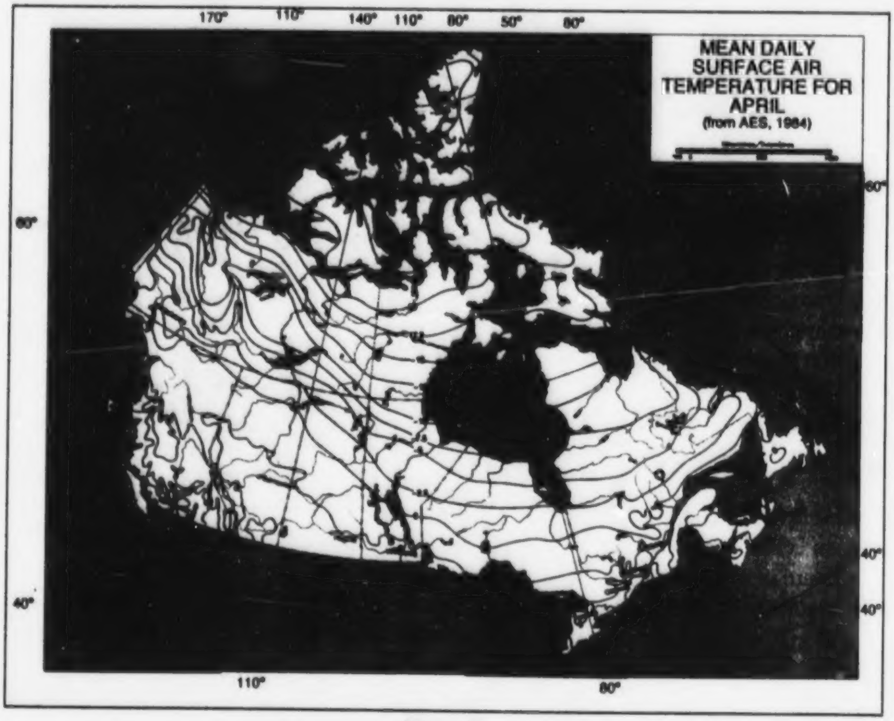

170°
110°
140°
110°
80°
50°
80°
MEAN DAILY
SURFACE AIR
TEMPERATURE FOR
APRIL
(from AES, 1984)
60°
60°
40°
40°
40°
110°
80°

Figure 5b.
Mean daily surface air temperature for January/April (from AES, 1984)

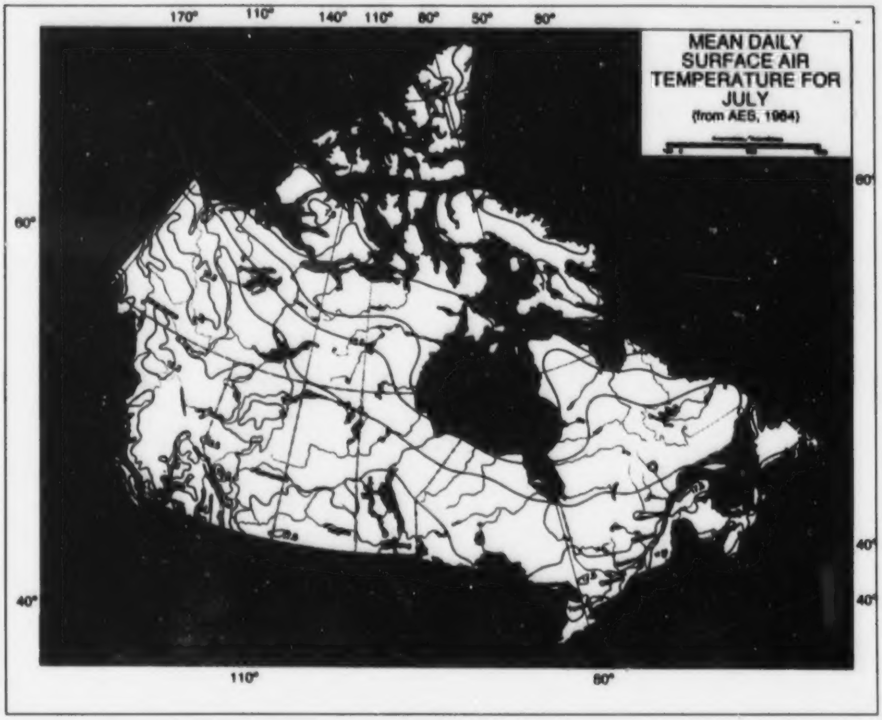

MEAN DAILY
SURFACE AIR
TEMPERATURE FOR
JULY
(from AES, 1984)
170°
110°
140°
110°
80°
50°
80°
60°
60°
40°
40°
40°
110°
80°

Figure 5c.

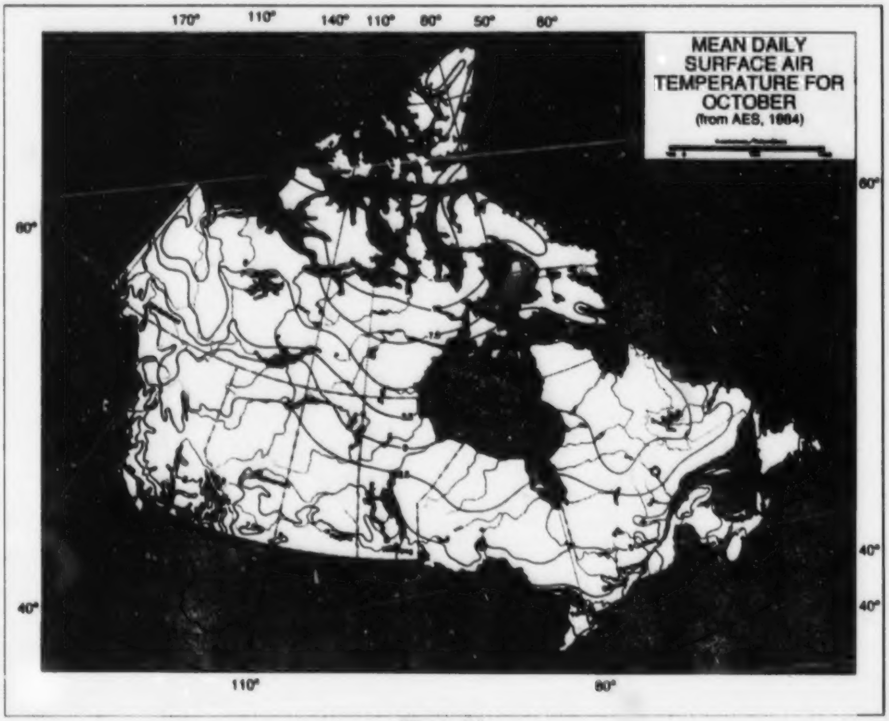

MEAN DAILY
SURFACE AIR
TEMPERATURE FOR
OCTOBER
(from AES, 1984)
170°
110°
140°
110°
80°
50°
80°
60°
60°
40°
40°
40°
110°
80°

Figure 5d.
Mean daily surface air temperature for July/October (from AES, 1984)

fall over the Arctic Islands (compared to winter) as ice begins to deteriorate and more moist air is able to penetrate from the south. Fog frequency increases generally and blowing snow frequency decreases.

July to August

Over the mainland, quite warm periods are possible with extreme high temperatures in excess of 30°C occurring, particularly in the Mackenzie area. Mean daily values across the Basin range from 10 to 18°C from northeast to southwest.

Elsewhere, the maritime influence of the sea and channels is a major control of the climate. By July, break-up is well advanced in Hudson Bay; in August, most of the waterways among the southerly Arctic Islands are also well-advanced into their seasons. Meanwhile further north, many channels remain almost icebound. As a consequence, warm, moist air masses entering the Arctic from the south are subject to cooling from below resulting in extensive low-lying cloud layers and fog. Over the islands of the Arctic, mean daily temperatures are fairly uniform at about 5°C except in the interior of the larger islands where they can be a further 5°C or so warmer. Extreme highs range from 20 to 25°C in the south to 15 to 18°C in the north.

This is the wettest time of year with monthly rainfall totals ranging from 40-50 mm over Mackenzie and Keewatin to 10-20 mm over the central Arctic Islands. Topography again plays a major role in high totals (60-80 mm) over the eastern Arctic coasts. Snowfall may occur in either of these months among the Islands, but amounts are light. In the southern Mackenzie District, thunderstorms and lightning are not uncommon.

September to early November

At the beginning of September, mean daily temperatures are already below freezing over the High Arctic Islands. By the end of the month, temperatures range from -15 to -20°C in the north to near 0°C over the southern islands to about 5°C in the southern mainland. A month and a half later, means have dropped by a further 10 to 15°C across the whole region.

This is the stormiest time of the year in the Arctic. The largest proportion of the annual snowfall (100 to 150 cm in the Mackenzie, 50-75 cm over the central Arctic Islands, over 200 cm on exposed eastern Arctic slopes) occurs during this period. Fogs are less frequent than in July and August, but visibility is lowered appreciably in snow storms.

Later into the season, ice cover increases so that open water is no longer a major cloud-producing factor and the cold, relatively clear climate generally associated with the Arctic night begins to take over. Freeze-over of most northern waterways is usually complete by November, but in the southern areas, open water can be a factor until December.

This is the period when the Arctic white-out starts to appear. A condition that occurs when diffuse white clouds blend into the shadowless, snow-covered landscape, the Arctic white-out frequently hampers air operations and ground travel as it makes judgement of distances very difficult. White-out conditions often occur in April or May as well.

Recent Climate Trends

Figure 10 shows the Canadian Climate Regions and the distribution of the 131 stations having temperature data in the Historical Canadian Climate Database (HCCD). Three of these climate regions comprise the Canada Country Study's Arctic Region. The HCCD was constructed from the National Climate Data Archive (NCDA) of the Atmospheric Environment Service, using climate stations that were selected on the basis of spatial distribution, length of record, data continuity, homogeneity assessments and other factors. The HCCD was assembled to provide climate researchers access to an initial but expanding data set that has been rigorously quality controlled, assessed for homogeneity (Gullett *et al.*, 1991), and adjusted, where necessary, to ensure regional representativeness. The data adjustments that were carried out had the effect of filtering out some of the "local" noise, thereby making the data suitable for use in regional scale analyses. Departures of annual and seasonal values from the 1951 to 1980 normal were calculated for the each location in all climate regions, and then averaged, to create regional series of departures from normal. Currently, the data are use-

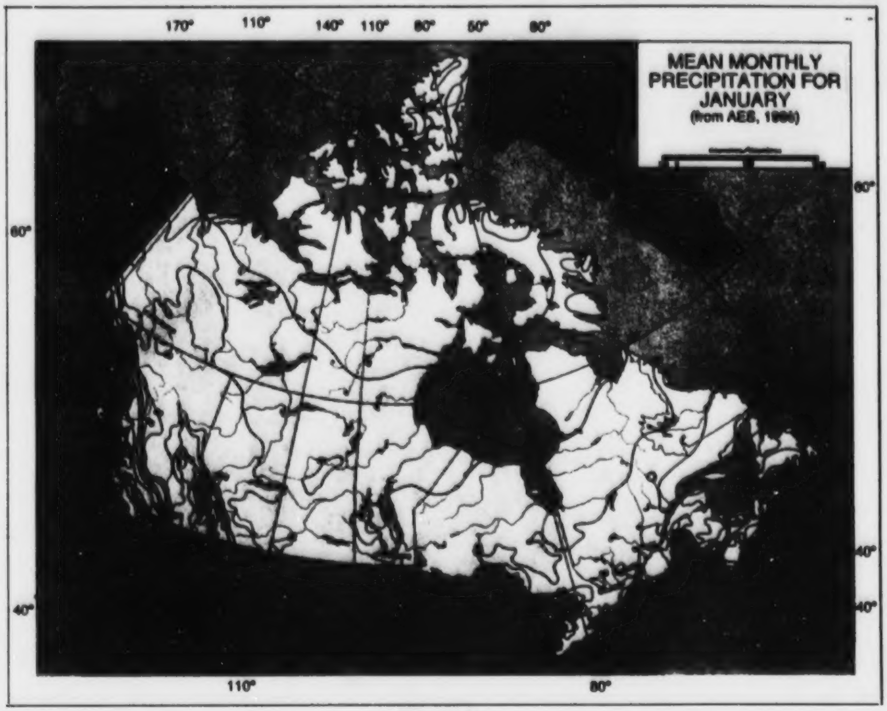

170°
110°
140°
110°
80°
50°
80°
MEAN MONTHLY PRECIPITATION FOR JANUARY
(from AES, 1986)
60°
60°
40°
40°
40°
110°
80°

Figure 6a.

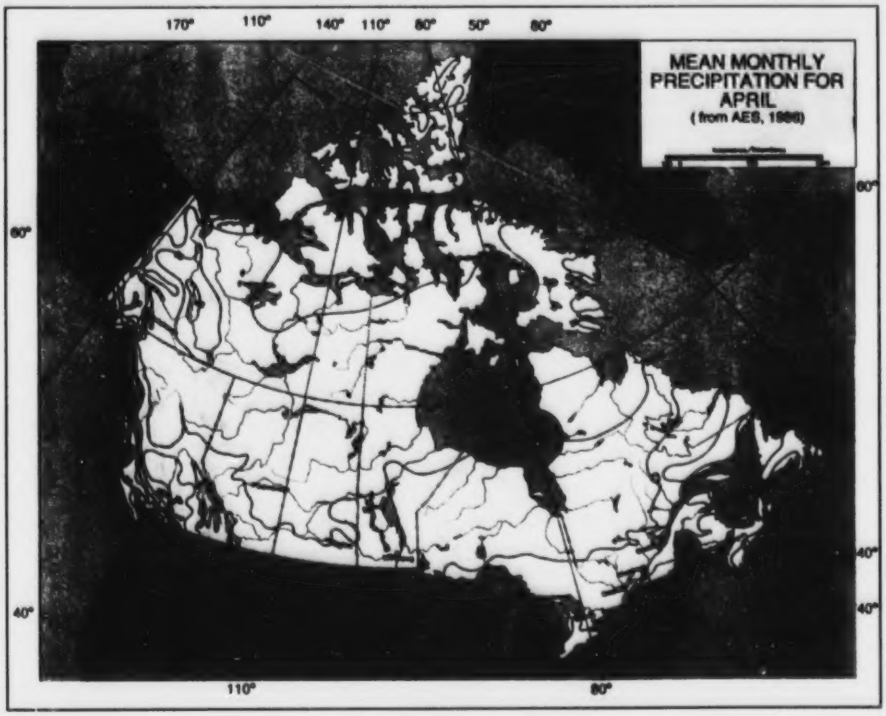

170°
110°
140°
110°
80°
50°
80°
MEAN MONTHLY PRECIPITATION FOR APRIL
(from AES, 1986)
60°
60°
40°
40°
40°
110°
80°

Figure 6b.
Mean monthly precipitation for January/April (from AES, 1986)

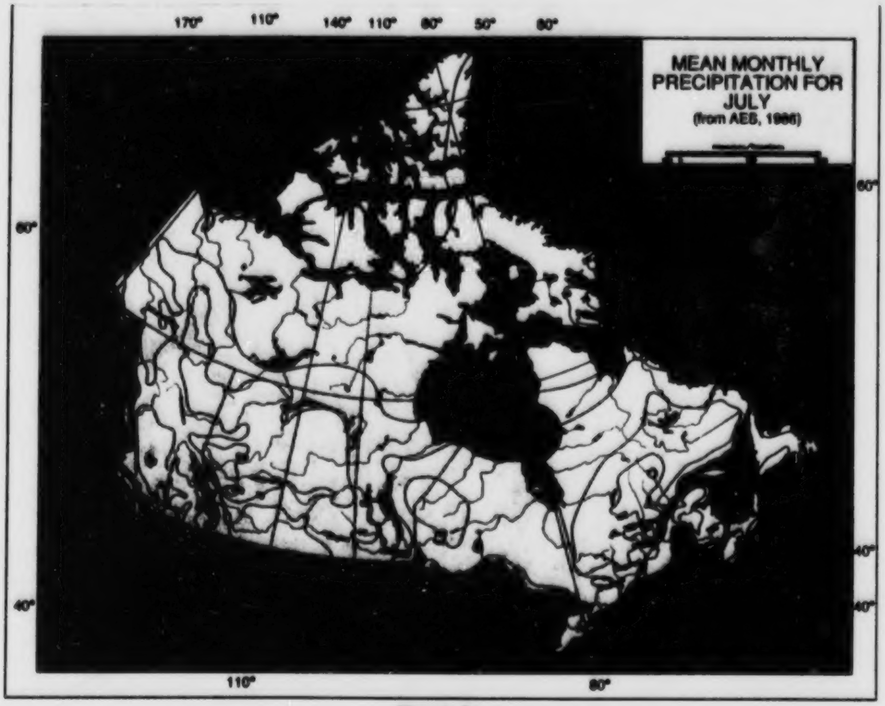

170°
110°
140°
110°
80°
50°
80°
MEAN MONTHLY
PRECIPITATION FOR
JULY
(from AES, 1986)
60°
60°
40°
40°
40°
110°
80°

Figure 6c.

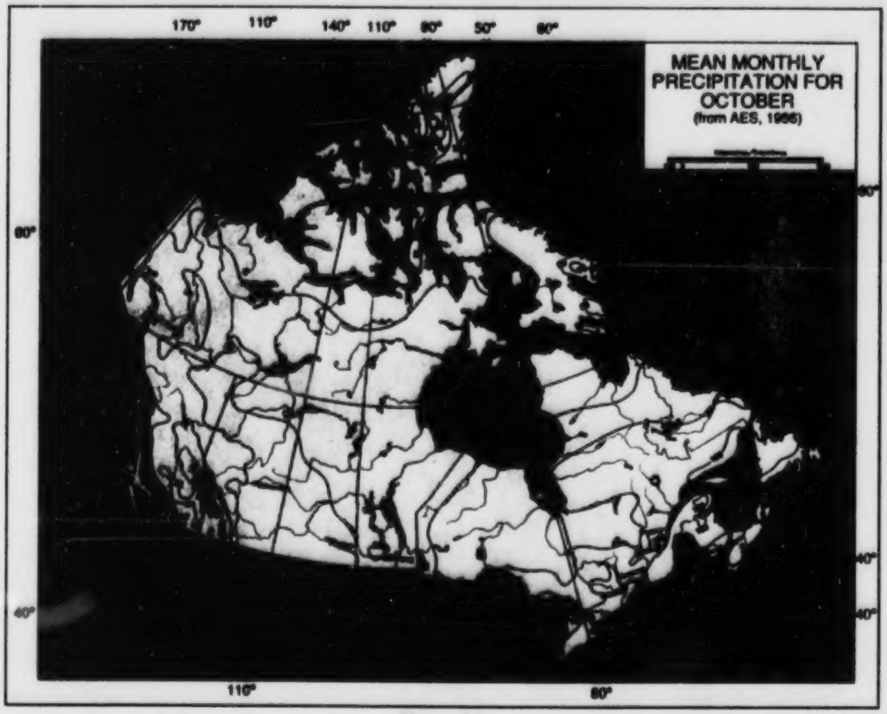

170°
110°
140°
110°
80°
50°
80°
MEAN MONTHLY
PRECIPITATION FOR
OCTOBER
(from AES, 1986)
60°
60°
40°
40°
40°
110°
80°

Figure 6d.
Mean monthly precipitation for July/October (from AES, 1986)

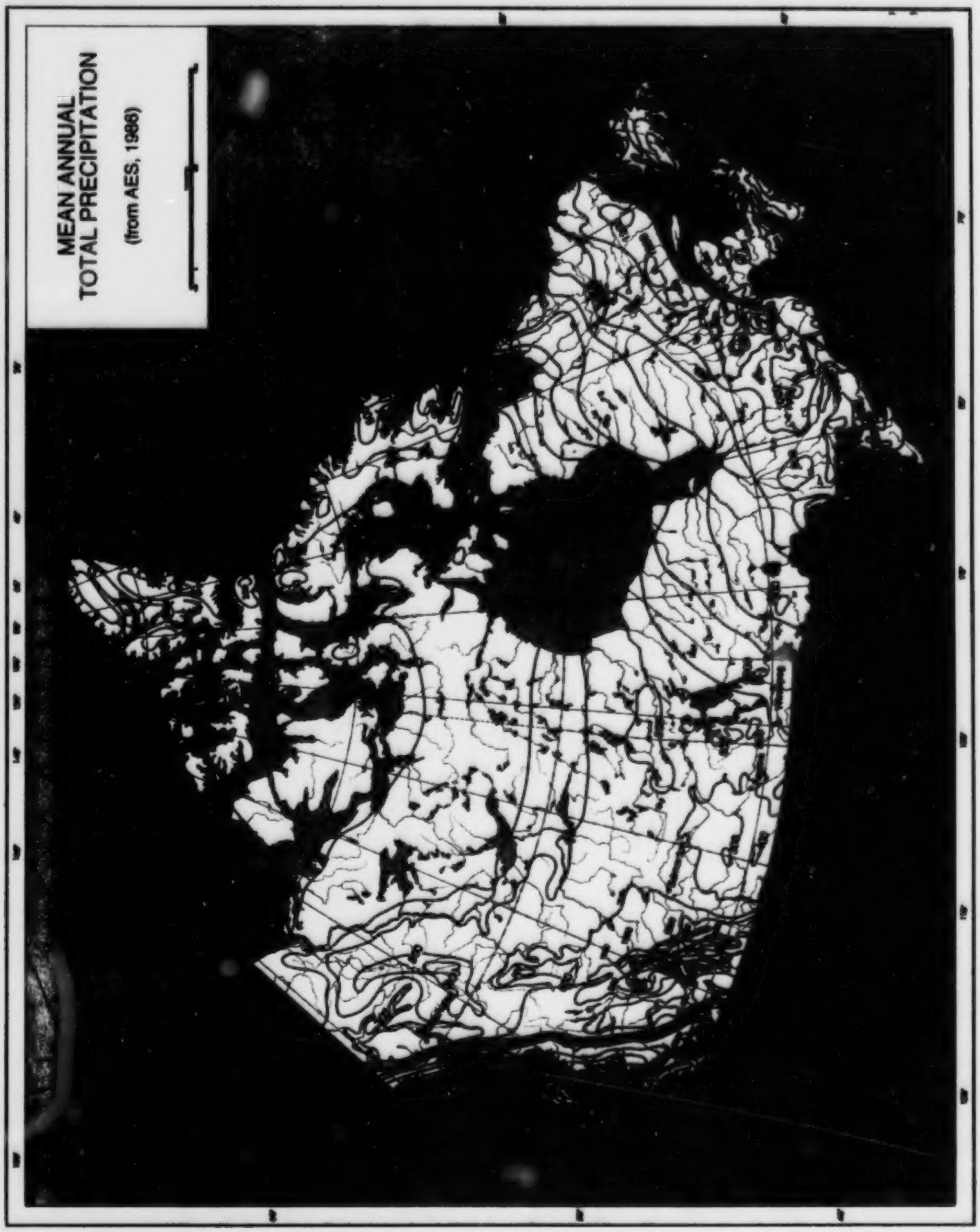

MEAN ANNUAL
TOTAL PRECIPITATION
(from AES, 1986)

Figure 7. Mean annual total precipitation (from AES, 1986)

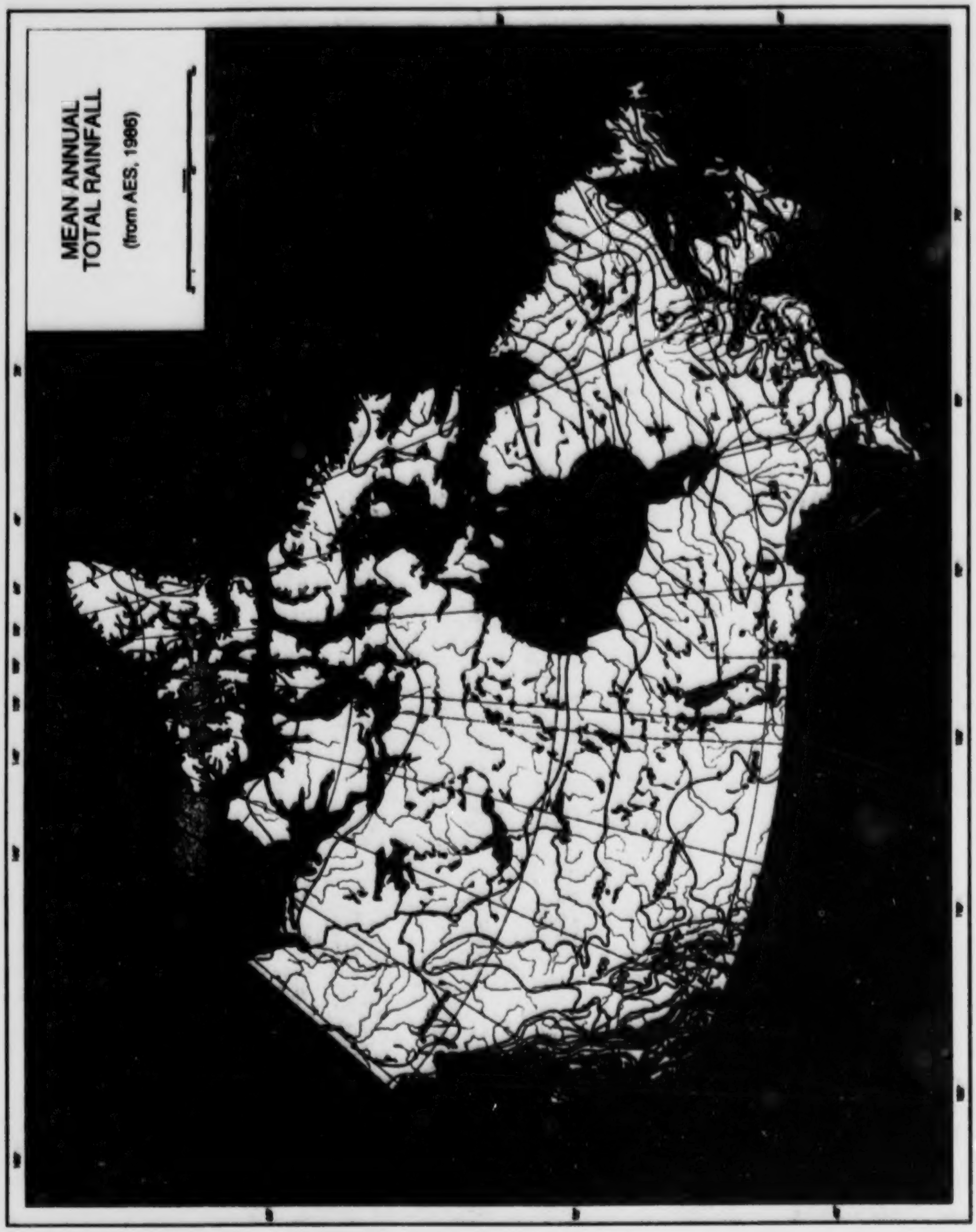

MEAN ANNUAL
TOTAL RAINFALL
(from AES, 1986)

Figure 8. Mean annual total rainfall (from AES, 1986)

MEAN ANNUAL
TOTAL SNOWFALL
(from AES, 1986)

Figure 9. Mean annual total snowfall (from AES, 1986)

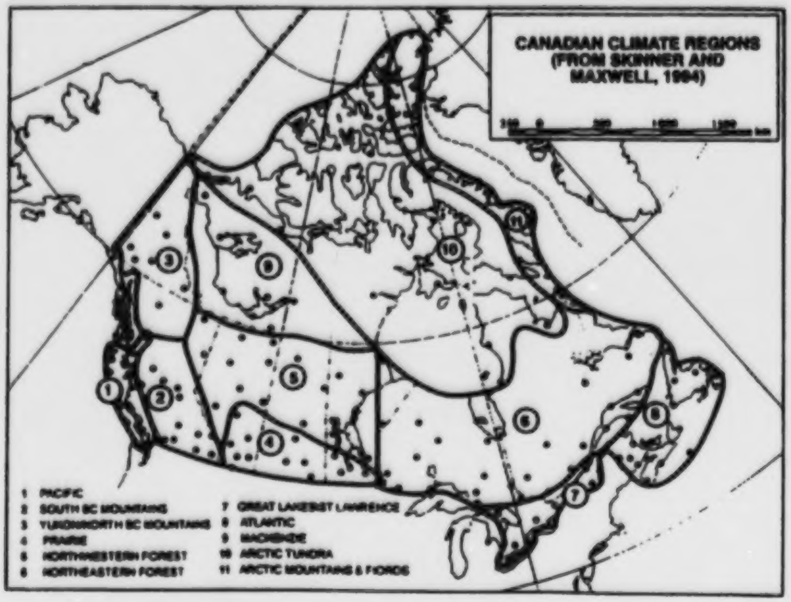

CANADIAN CLIMATE REGIONS
(FROM SKINNER AND
MAXWELL, 1994)
1
2
3
4
5
6
7
8
9
10
11
1 PACIFIC
2 SOUTH BC MOUNTAINS
3 YUKON/NORTH BC MOUNTAINS
4 PRAIRIE
5 NORTHWESTERN FOREST
6 NORTHEASTERN FOREST
7 GREAT LAKES/ST LAWRENCE
8 ATLANTIC
9 MACKENZIE
10 ARCTIC TUNDRA
11 ARCTIC MOUNTAINS & FIORDS

Figure 10. Canadian climate regions (from Skinner and Maxwell, 1994)

ful for large regional and national scale analyses over seasonal and annual durations (Skinner and Gullett, 1993).

Air Temperature

Figure 11 shows the time series of annual daily mean temperature departures from the 1951 to 1980 average for the three Arctic climate regions. These are accompanied by ten-year running average filters to denote trends (Skinner and Maxwell, 1994).

The western region (Mackenzie), has a longer observational record than the two eastern regions - Arctic Tundra and Arctic Mountains and Fjords. This is related directly to the history of settlement in each of these areas. The western region reflects the national pattern of warming into the 1940s, followed by cooling into the 1970s, and a resumption of warming through the 1980s. Overall, the region has warmed by some 1.5°C over the past 100 years. The two eastern regions show a similar pattern of warming followed by cooling into the 1970s, but no warming after that. In fact, the Arctic Tundra region has experienced near normal temperatures since that time while the Arctic Mountains and Fjords region has continued to cool.

Figure 12 shows seasonal time series of daily mean temperature departures for the Mackenzie climate region. The national pattern is reflected in the winter and spring series with pronounced warming during both of these seasons occurring since the 1970s. A slight increasing trend is evident during the summer season. Autumn cooling is evident since the 1940s.

Figure 13 shows seasonal time series of daily mean temperature departures for the Arctic Tundra climate region. Although the time series are shorter, there is evidence of warming into the 1940s during the winter and spring seasons. During winter, however, there is no trend at all after the 1940s, and during spring there was a cooling trend into the 1960s and then no trend after that. A slight warming trend is evident during the summer season and no apparent trend during the autumn.

Figure 14 shows seasonal time series of daily mean temperature departures for the Arctic Moun-

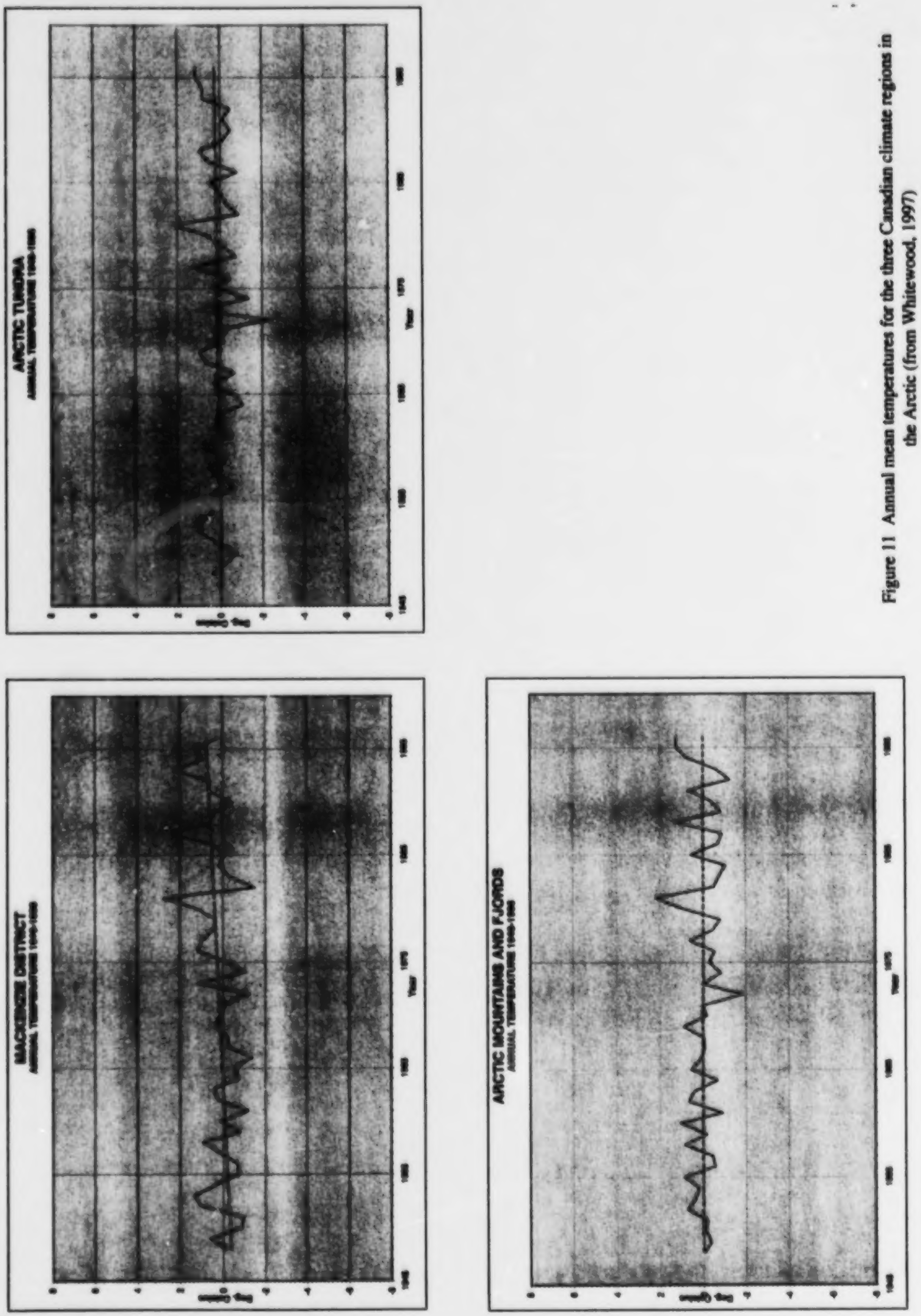


Figure 11 Annual mean temperatures for the three Canadian climate regions in the Arctic (from Whitewood, 1997)

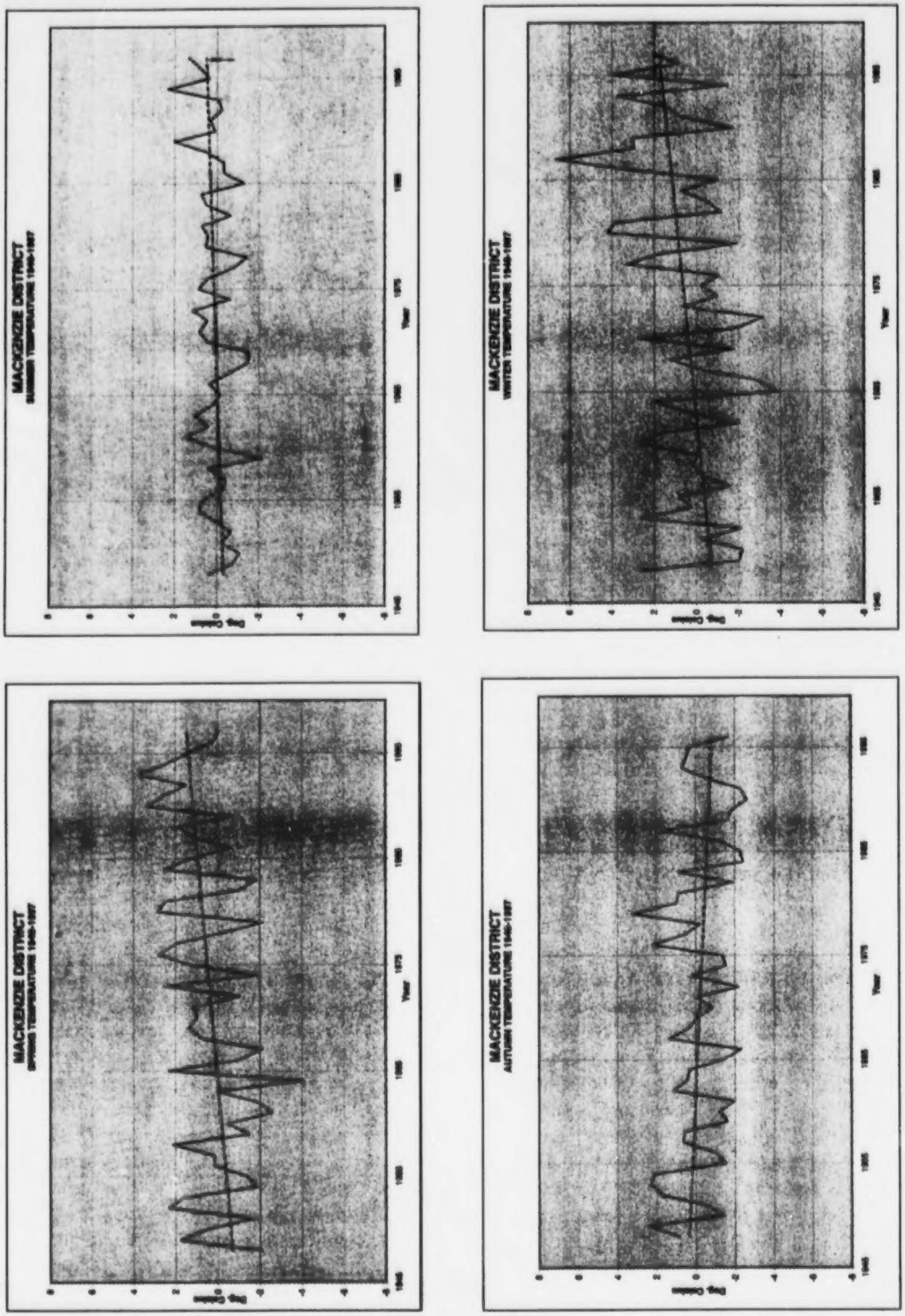


Figure 12 Seasonal mean temperatures for the Mackenzie climate region, 1948 to 1997 (from Whitewood, 1997)

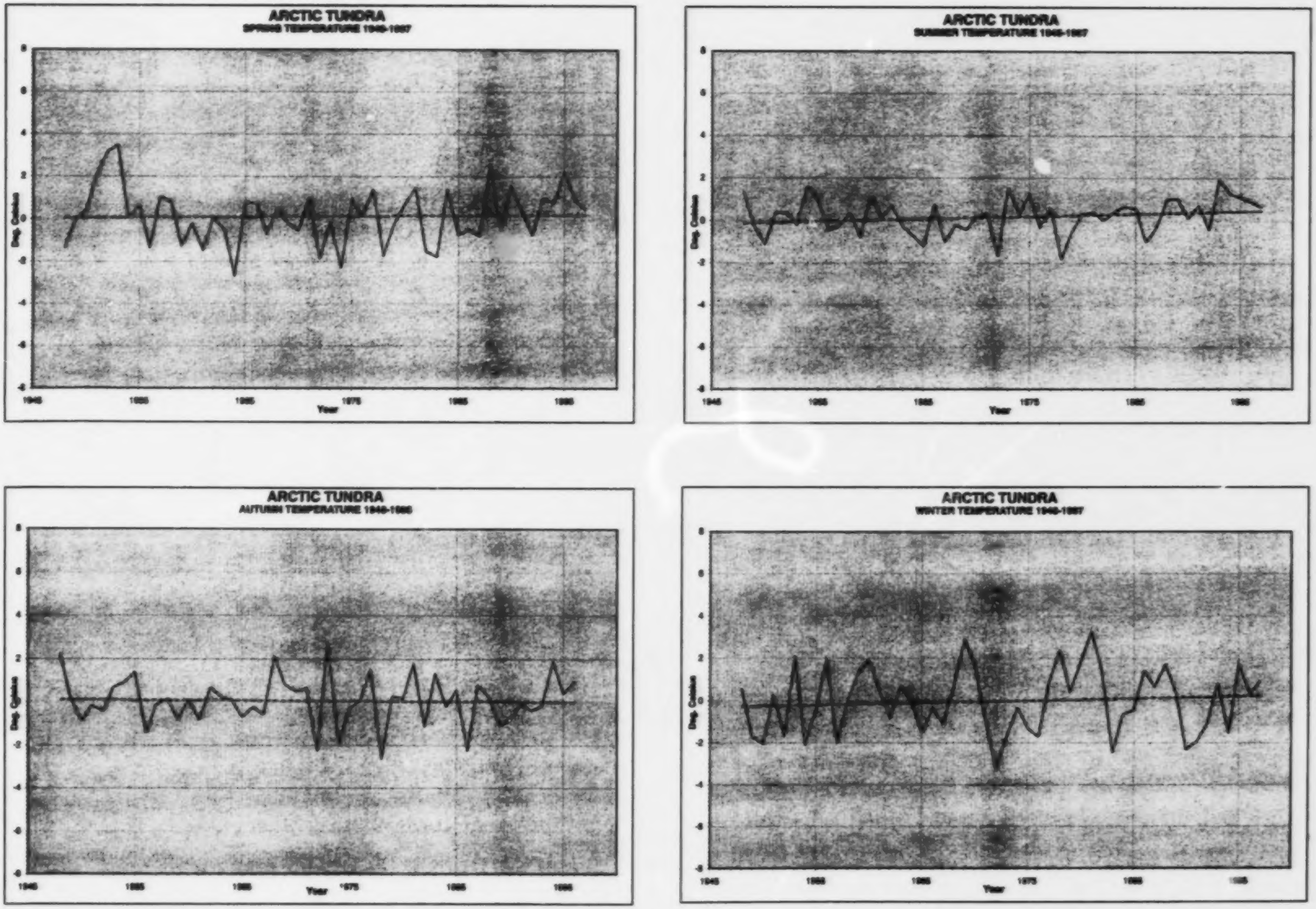


Figure 13. Seasonal mean temperatures for the Arctic Tundra climate region 1948 to 1997 (from Whitewood, 1997)

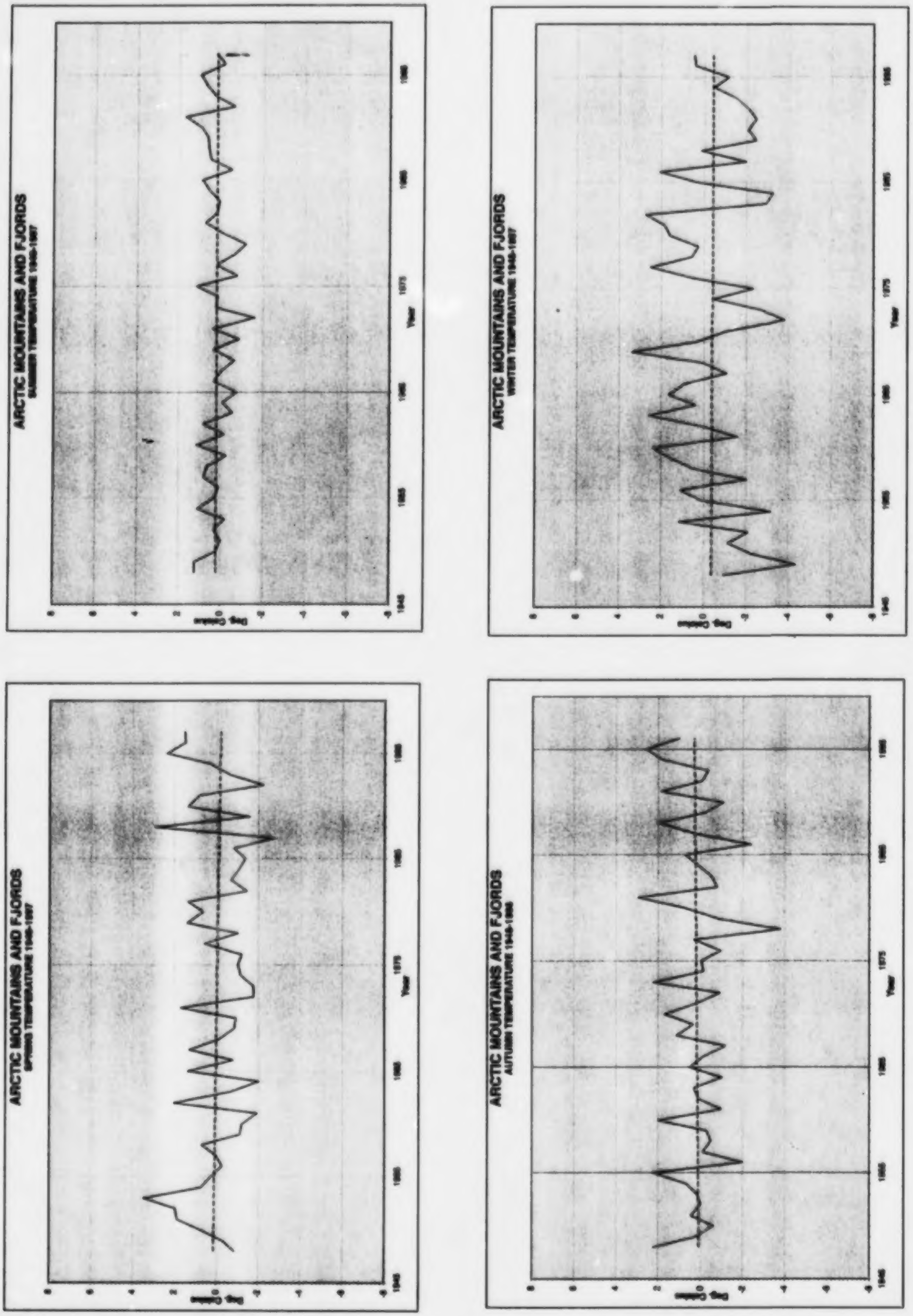


Figure 14 Seasonal mean temperatures for the Arctic Mountains and Fjords climate region, 1948 to 1997 (from Whitewood, 1997)

tains and Fjords climate region. Time series for this region are shorter, beginning in 1946. During winter, there was warming into the early 1960s followed by a cooling trend until the present. During spring, there has been a cooling trend for the entire period of record. There has been a slight warming trend during the 1980s during the summer season and no apparent trend during the autumn.

In addition to these recent areal surface temperature trends, wintertime surface-based inversions at five Arctic locations (Alert, Eureka, Mould Bay, Sachs Harbour, and Inuvik) have decreased significantly in depth over the past couple of decades, accompanied in most cases by increased surface temperature (Bradley *et al.*, 1992,1993).

Precipitation

During the period 1948-1992, there has been a trend towards increasing precipitation in many regions of Canada (Environment Canada, 1995) The greatest increases in the Arctic have been in the tundra area of the Keewatin District extending northward into the central Arctic Islands. Slight increases occurred in the Mackenzie District, but the records suggest no discernible change among the Arctic mountains and fjords of the eastern Arctic (Figures 15 to 17).

Based on satellite data, snow cover shows a trend to lesser total extent in North America in spring during the 1980s as compared to the previous decade (Robinson and Dewey, 1990), a trend which continued into the early 1990s (Robinson *et al.*, 1993) In the central tundra area of the Canadian Arctic, four locations (Tuktoyaktuk, Coppermine, Cambridge Bay and Hall Beach) have experienced a trend to earlier snowmelt beginning in the late 1960s and continuing through the early 1990s. One location in the eastern Arctic (Clyde) suggested a later snowmelt (Foster, 1989; Maxwell, 1997).

Sea-Level Pressure

A comparison of annual mean pressures over the Arctic Basin during the periods 1979-1986 and 1987-1994 has shown the values for the more recent period to be 3.0 to 4.6 mb lower than for the earlier period (Walsh *et al.*, 1996). Over the Canadian Arctic Islands, the decrease is in the range of 1 to 3 mb. Each calendar month shows the decline; with the largest decreases having occurred during the January-to-March period. The decrease in pressure is reflected in increased cyclonicity of the wind flow in the region. Over the mainland Arctic, there is a northeast-to-southwest gradient from small decreases to small increases in pressure. This is in accord with the findings of a strengthening in the western North America ridge in the region of about 50°N latitude/110°W longitude (Chen *et al.*, 1992).

Scenarios of Climate Change

The results of the IPCC Second Assessment Report (IPCC, 1995) indicated that for a doubling of the atmospheric concentration of greenhouse gases alone, the GCMs project an increase in global mean temperature relative to the present of from 1 to 4.5°C by 2100. This projection is based on the assumption that the atmospheric aerosol content remains constant at 1990 levels. Incorporating the possible effects of future changes in aerosol content into the model simulations alters the projected temperature increase to a 1 to 3.5°C range by 2100.

All GCM scenarios of climate change under a doubled atmospheric concentration of carbon dioxide show the following features pertinent to the Arctic: greater warming over the land than the sea; reduced warming or even cooling over part of the northern North Atlantic Ocean; maximum warming in high northern latitudes in winter, but little warming in summer; and increased precipitation and soil moisture in high latitudes in winter (Everett *et al.*, 1997).

The results from the GCM of the Canadian Centre for Climate Modelling and Analysis (CCC92) as shown in Figures 18 to 21 indicate the following temperature changes for the Arctic Region.

For the period December through February, temperature increases range from 5 to 7°C going from west to east on the mainland. Temperatures increases are progressively higher over Hudson Bay and northward into the High Arctic Islands, reaching values near 10°C over central Hudson Bay and over the Arctic Ocean northwest of the Islands. During March-to-May, temperature increases are generally 3 to 5°C across the whole region, with a

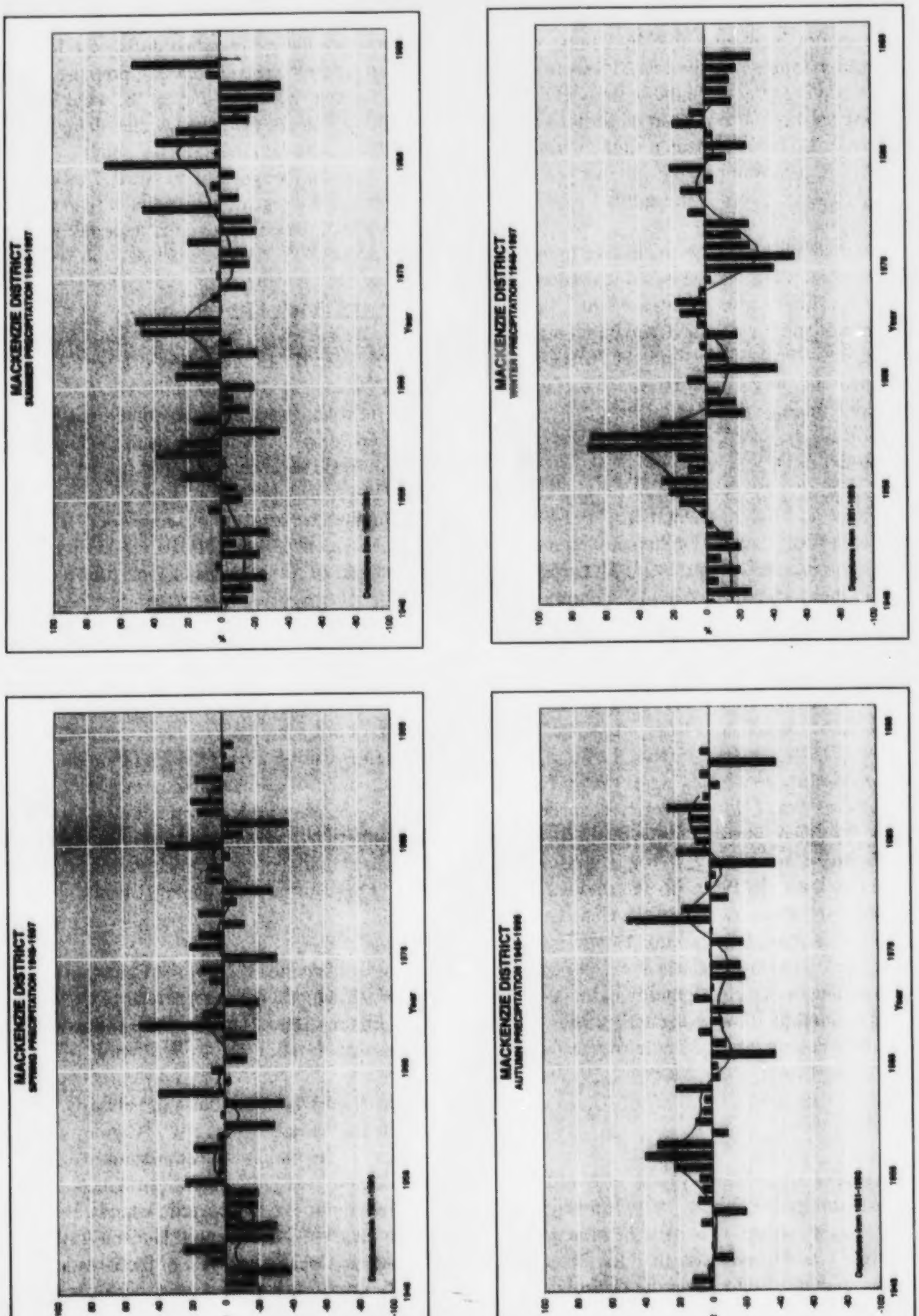


Figure 15. Seasonal precipitation departures for the Mackenzie climate region, 1948 to 1997 (from Whitewood, 1997)

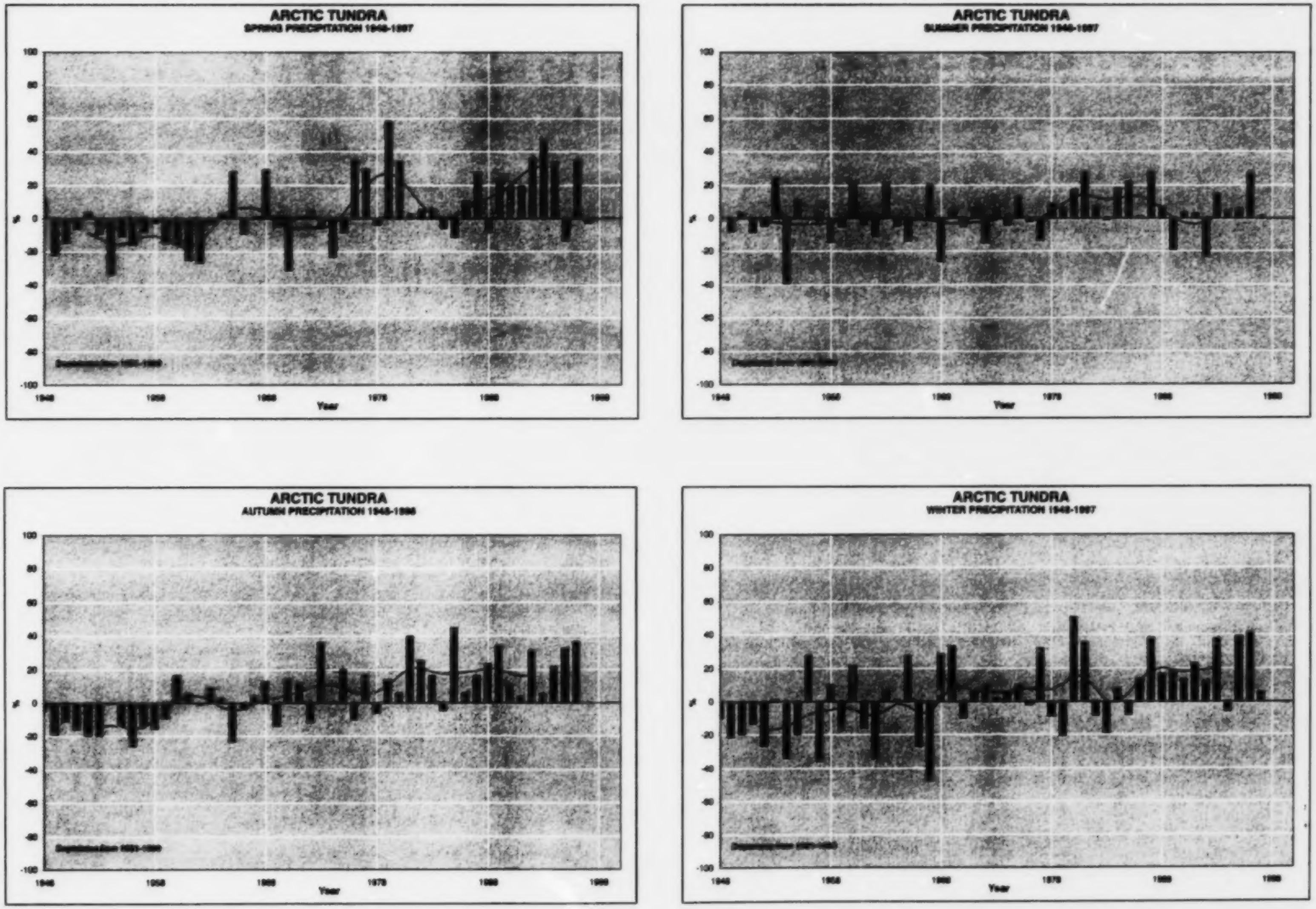


Figure 16. Seasonal precipitation departures for the Arctic Tundra climate region, 1948 to 1997 (from Whitewood, 1997)

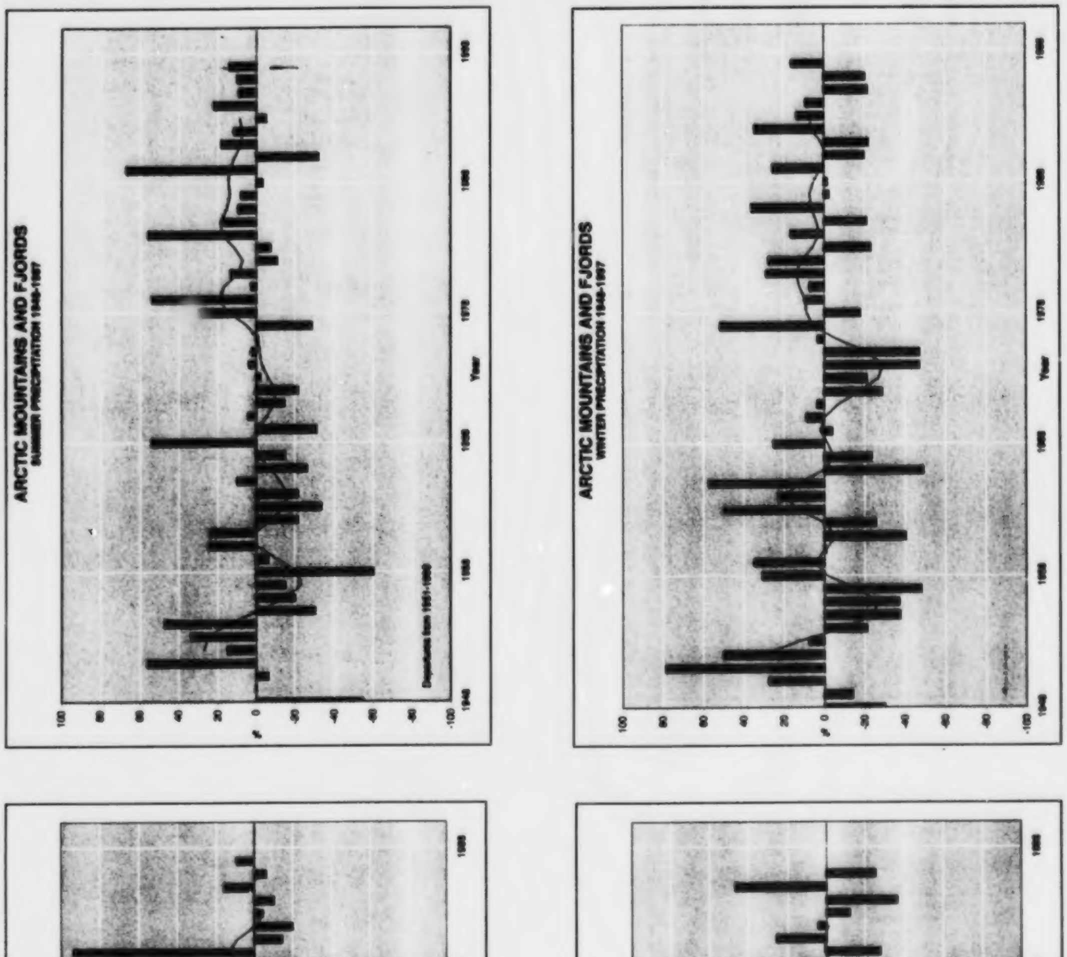


Figure 17. Seasonal precipitation departures for the Arctic Mountains and Fjords climate region, 1948 to 1997 (from Whitewood, 1997)

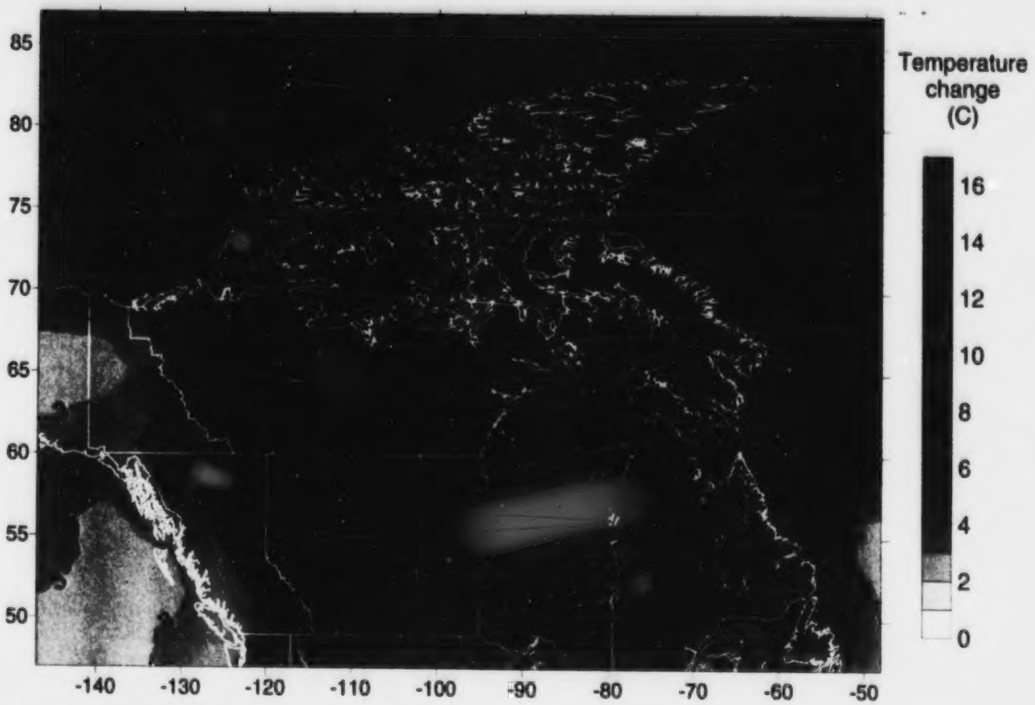


Figure 18. Projected change in mean winter (Dec.-Feb.) temperature based on the CCC GCM (1992) for a doubling of atmospheric CO_2 (from Taylor, 1997)

maximum just above 5°C over northwestern Keewatin District. For June-to-August, there is broad area of temperature increase near 5°C over much of Keewatin and the southern islands. Increases are reduced to 1 to 2°C over northern Hudson Bay and the High Arctic Islands. In September-to-November, temperature increases range from 3 to 4°C near 60°N increasing with latitude to maximum values of 8 to 9°C over the High Arctic Islands.

Precipitation scenarios from the CCC92 GCM (Figures 22 to 25) suggest a general increase in precipitation of between 0 and 25% for a doubling of atmospheric carbon dioxide. The higher magnitudes tend to occur in the summer and autumn months. In winter and spring, widespread increase is less pronounced with some small areas of the Canadian Arctic - mainly in the northern Hudson Bay, northwestern Baffin Bay and Victoria and Banks Islands areas - possibly experiencing less precipitation than at present.

With both increased temperature in the Arctic, snowfall in the early autumn or spring may become rain or freezing rain. Similarly, snow cover melt may be advanced by weeks and many late-lying snowbanks which are currently important local water sources for maintaining patchy wetlands in the low Arctic or sustaining moist zones on high Arctic slopes would be eliminated (Woo, 1990)

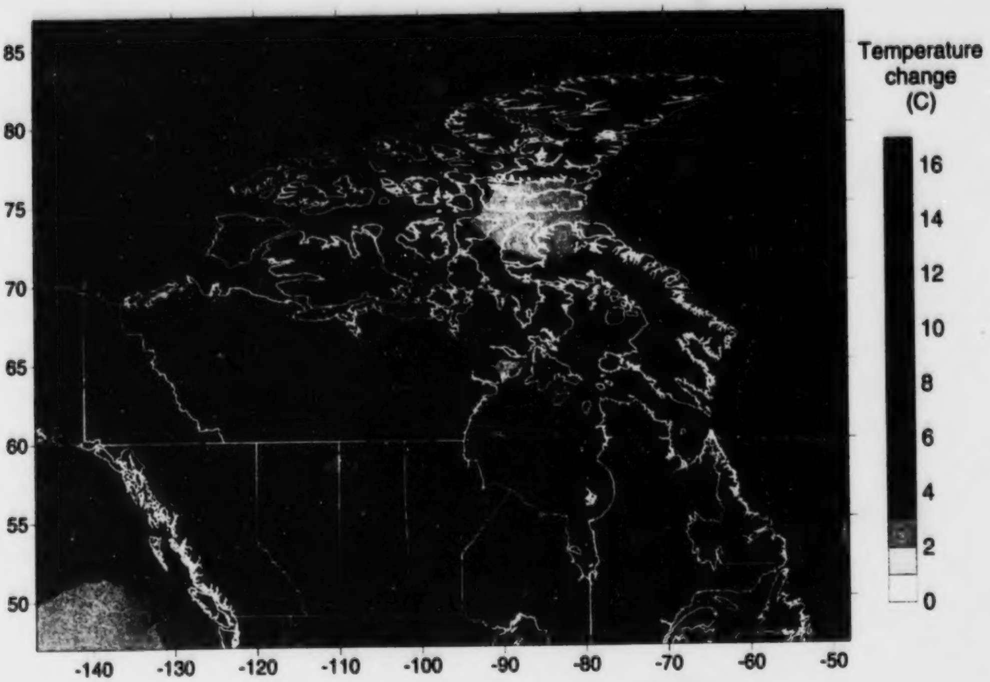

85
80
75
70
65
60
55
50
-140
-130
-120
-110
-100
-90
-80
-70
-60
-50
Temperature change (C)
16
14
12
10
8
6
4
2
0

Figure 19. Projected change in mean spring (Mar.-May) temperature based on the CCC GCM (1992) for a doubling of atmospheric CO_2 (from Taylor, 1997)

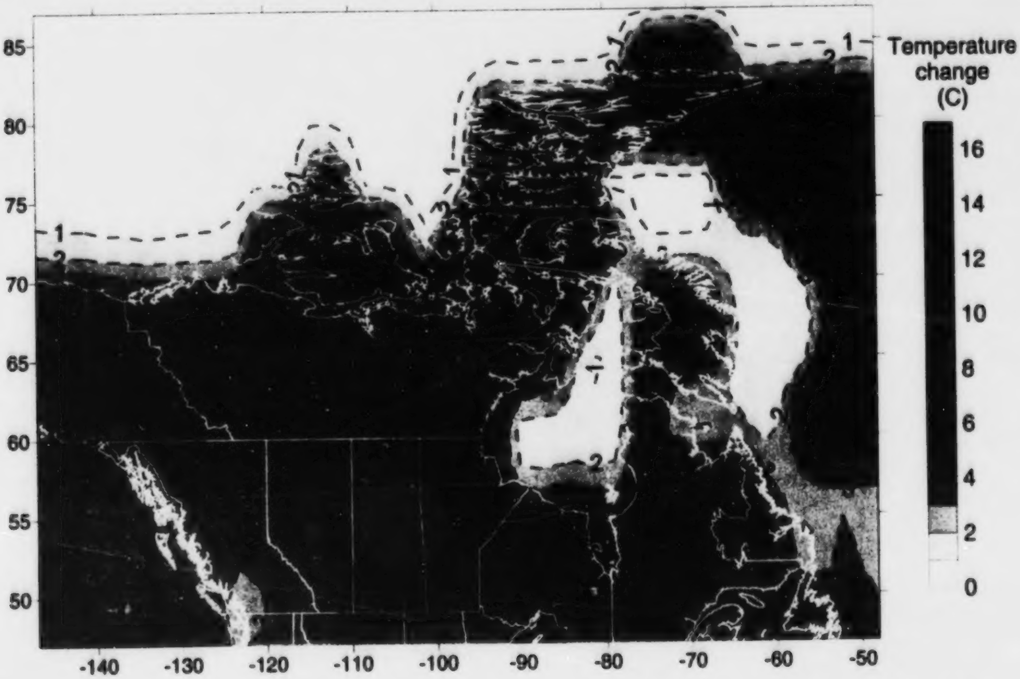

85
80
75
70
65
60
55
50
-140
-130
-120
-110
-100
-90
-80
-70
-60
-50
1
2
Temperature change (C)
16
14
12
10
8
6
4
2
0

Figure 20. Projected change in mean summer (Jun.-Aug.) temperature based on the CCC GCM (1992) for a doubling of atmospheric CO_2 (from Taylor, 1997)

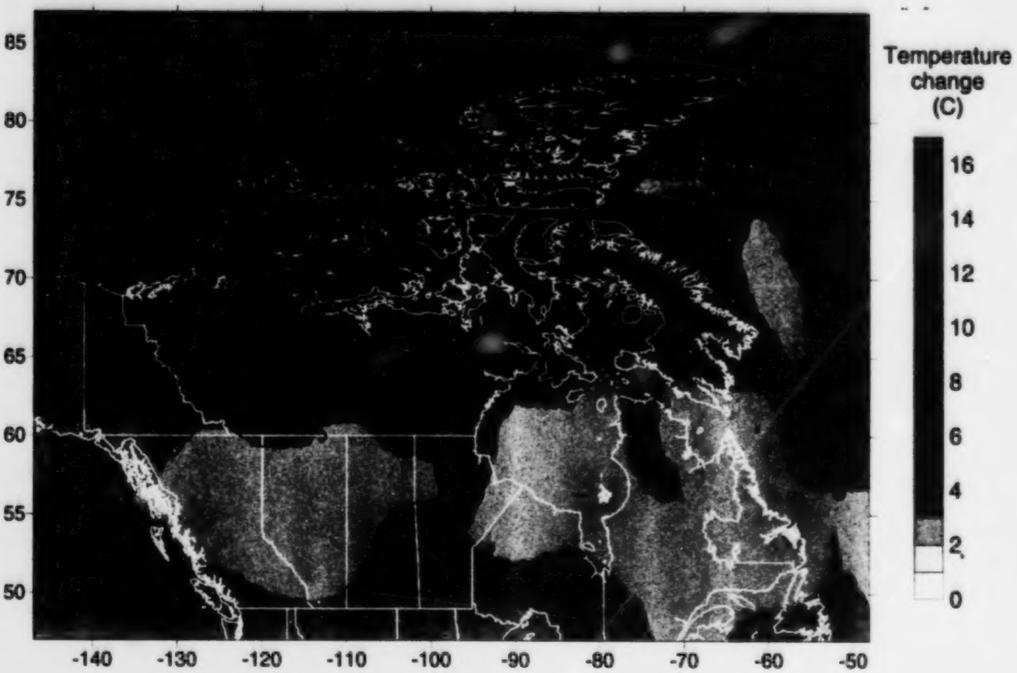

85
80
75
70
65
60
55
50
-140
-130
-120
-110
-100
-90
-80
-70
-60
-50
Temperature change (C)
16
14
12
10
8
6
4
2
0

Figure 21. Projected change in mean autumn (Sep.-Nov.) temperature based on the CCC GCM (1992) for a doubling of atmospheric CO_2 (from Taylor, 1997)

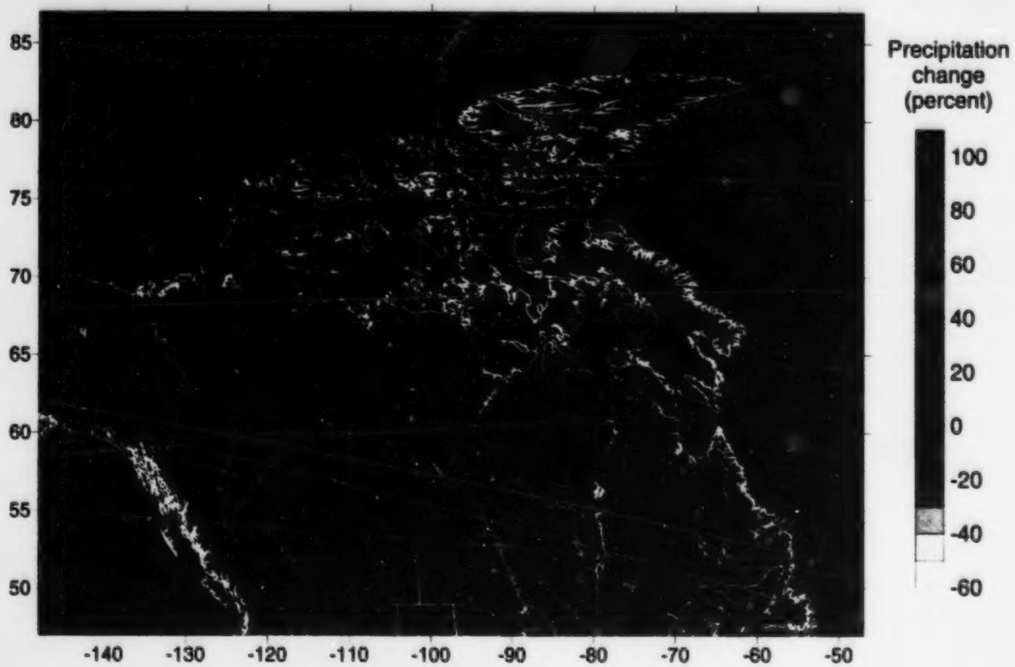

85
80
75
70
65
60
55
50
-140
-130
-120
-110
-100
-90
-80
-70
-60
-50
Precipitation change (percent)
100
80
60
40
20
0
-20
-40
-60

Figure 22. Projected change in mean winter (Dec.-Feb.) precipitation based on the CCC GCM (1992) for a doubling of atmospheric CO_2 (from Taylor, 1997)

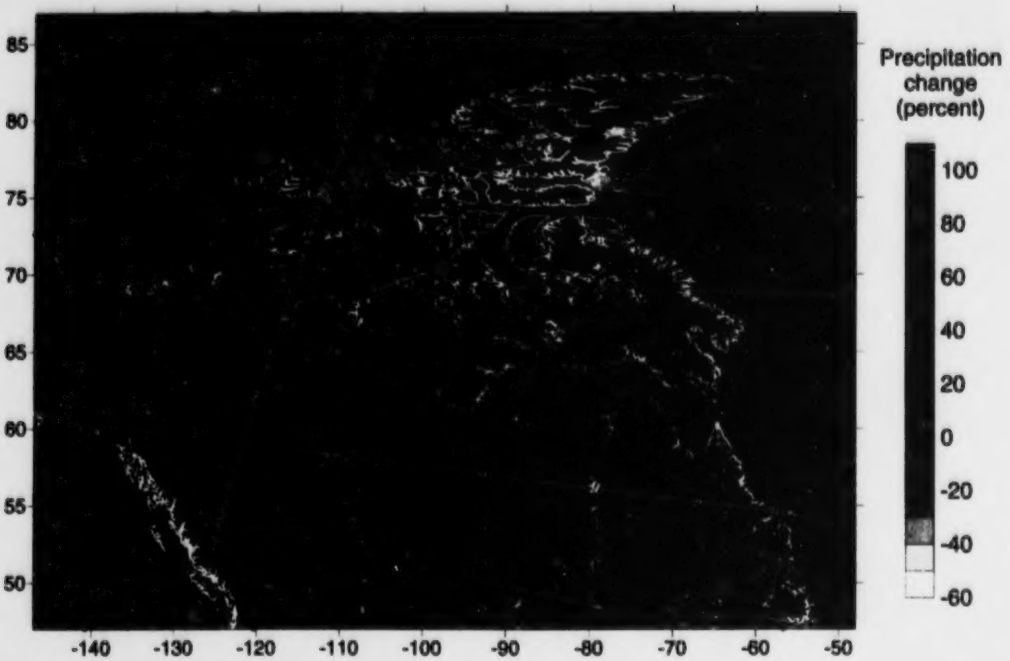

85
80
75
70
65
60
55
50
-140
-130
-120
-110
-100
-90
-80
-70
-60
-50
Precipitation change (percent)
100
80
60
40
20
0
-20
-40
-60

Figure 23. Projected change in mean spring (Mar.-May) precipitation based on the CCC GCM (1992) for a doubling of atmospheric CO_2 (from Taylor, 1997)

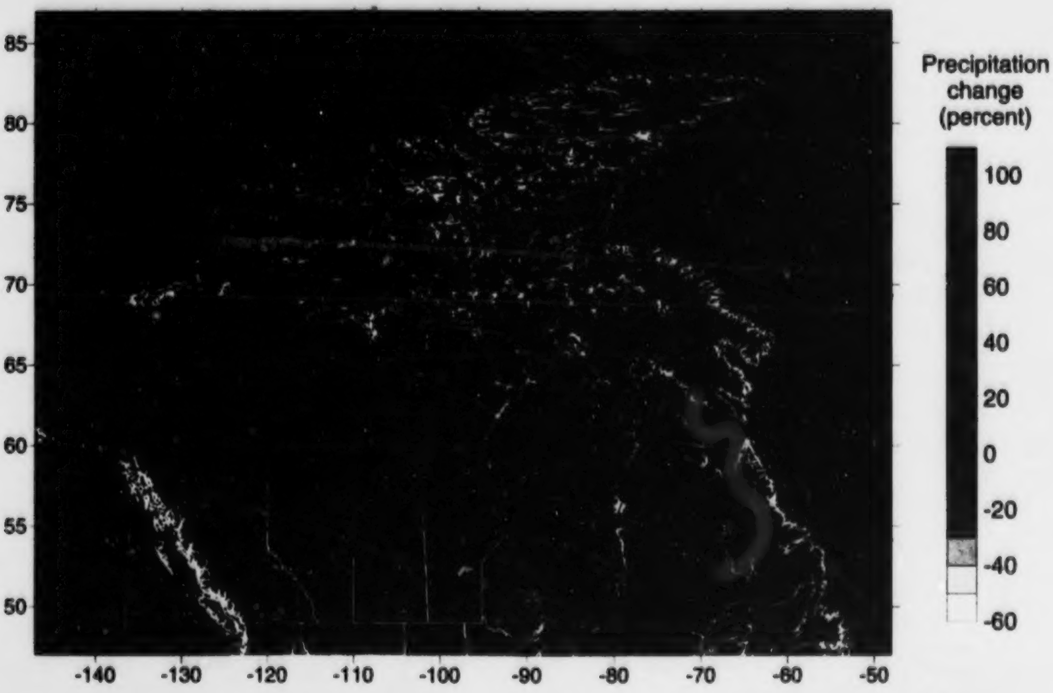

85
80
75
70
65
60
55
50
-140
-130
-120
-110
-100
-90
-80
-70
-60
-50
Precipitation change (percent)
100
80
60
40
20
0
-20
-40
-60

Figure 24. Projected change in mean summer (Jun.-Aug.) precipitation based on the CCC GCM (1992) for a doubling of atmospheric CO_2 (from Taylor, 1997)

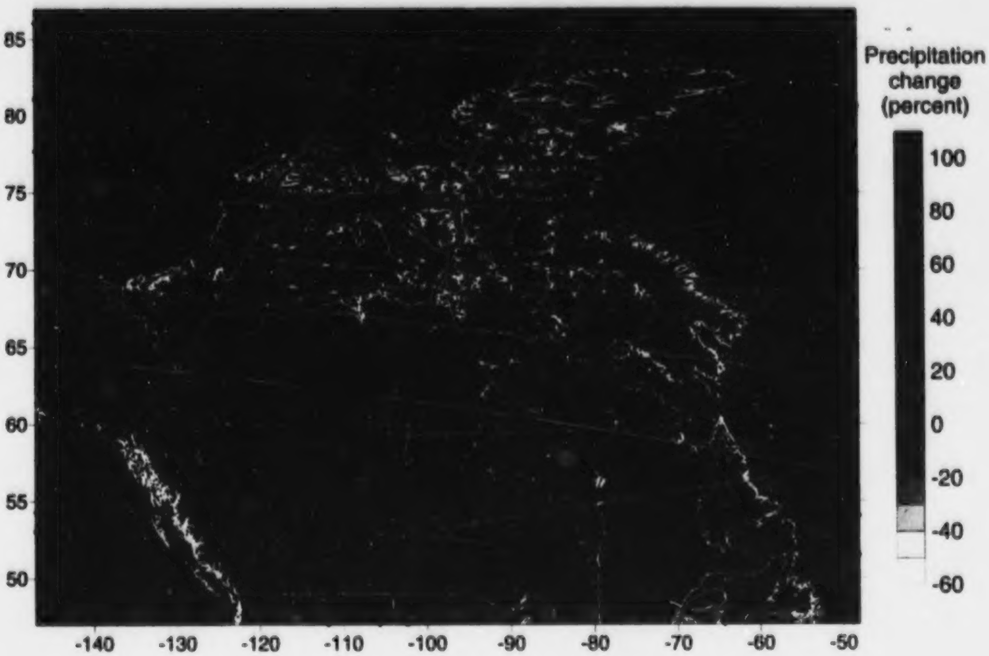

85
80
75
70
65
60
55
50
-140
-130
-120
-110
-100
-90
-80
-70
-60
-50
Precipitation change (percent)
100
80
60
40
20
0
-20
-40
-60

Figure 25. Projected change in mean autumn (Sep.-Nov.) precipitation based on the CCC GCM (1992) for a doubling of atmospheric CO_2 (from Taylor, 1997)

D. ARCTIC IMPACTS AND ADAPTATION

Aspects of the Physical Environment

Hydrology

A convenient way to look at hydrology in the Canadian Arctic is through consideration of the water balance for permafrost regions. The components of that balance are: precipitation (rainfall and snowmelt), glacier melt, ground-ice melt, evaporation/evapo-transpiration, runoff (surface and subsurface flow), and the change in storage. The first three of these balance with the last three. In the following paragraphs, these components are examined, with the exception of precipitation (considered above) and ground ice (considered later under permafrost).

Glacier Melt

Present Regime and Trends

The Canadian Arctic contains the largest glacier cover in the Northern Hemisphere outside of Greenland. Glaciers or ice caps are found on Baffin, Devon, Ellesmere, Axel Heiberg, Meighen, and Melville Islands. There is a program measuring the winter accumulation and summer ablation that has continued up to the present at several of the glaciers since about 1960, resulting in a number of series of annual mass-balance values. In all instances, this 35-year period has been one of modest glacial melt, in a range of 0.05 to 0.39 m water equivalent per year. There is no persistent trend in the data (Koerner, 1996).

Impacts of Climate Change

Most glaciers in the world are more sensitive to changes in temperature than any other climatic element; however, the complex dependence of glacier mass balance on precipitation and radiation as well as temperature makes it difficult to define their sensitivity to climate change (IPCC, 1995). In the Canadian High Arctic, mass-balance and ice-core melt studies have shown that when the circumpolar vortex shifts to the Asian side of the Arctic Ocean and the North American trough is replaced by a blocking ridge, high-Arctic glaciers experience high melt (Alt, 1987).

Although about one-third to one-half of presently existing mountain glaciers around the world are expected to disappear with anticipated warming over the next 100 years, at high altitudes and high latitudes such as in Arctic Canada, glaciers and ice caps seem likely to change little in overall size (IPCC, 1995). Enhanced melting at lower altitudes in summer would likely be combined with increased accumulation in higher zones. In an analogous situation during warmer parts of the Holocene, some Canadian Arctic glaciers actually grew due to such increased precipitation (Miller and de Vernal, 1992).

Evaporation/Evapotranspiration

Present Regime

Figure 26 shows derived annual evapotranspiration for Canada. In comparison with the annual precipitation shown in Figure 7, evapotranspiration amounts to about 50% of precipitation across the mainland area of Arctic Canada and somewhat less among the Arctic Islands. In general, evapotranspiration is greatest during the summer, especially in the areas of low relief characterized by numerous bogs and lakes where the evapotranspiration-to-precipitation ratio can exceed 1 (Woo *et al.*, 1992). For larger, deeper water bodies, heat storage becomes important so that in the autumn, only such bodies continue to produce significant evaporation.

The presence of peat in extensive wetland areas of the Arctic mainland controls the availability of moisture for the evaporation process there. Further to the north, evaporative losses due to transpiration decrease due to the lower vegetative density and the increasing proportion of mosses and lichens.

Snow sublimation is also a mechanism for moisture loss to the atmosphere. It is likely to be most significant during the spring high-radiation period, especially in high-wind, low-relief areas such as the northern Keewatin and in areas subject to foehn-like winds such as the mountainous zones of the Arctic Islands (Prowse and Ommanney, 1990).

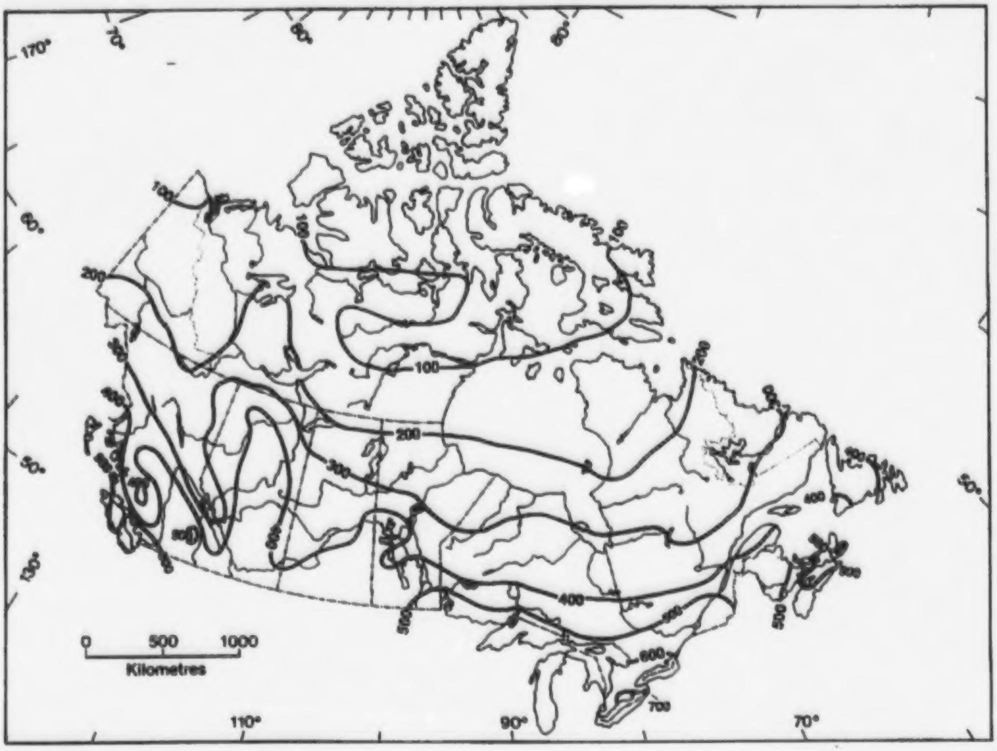


Figure 26. Derived annual evapotranspiration (from Prowse and Ommanney, 1990)

Impacts of Climate Change

A warmer atmosphere and longer thaw period will be conducive to increased evaporation in the Canadian Arctic. This should be particularly noticeable for lakes and ponds whose ice cover should become thinner and of shorter duration (Woo, 1990). Over wetlands, the overall impact is less clear. In the short term, evaporation should increase, but in the longer term, as sub-surface permafrost degrades and can no longer serve as an impermeable layer for maintaining high ground moisture levels, a reduction in wetland coverage will be favoured resulting in decreased evaporation. A mitigating factor may be the very low to non-existent hydraulic gradients. The evolution of bog to fen accompanying permafrost thaw in the northern prairie provinces does not appear to have substantial drying occurring (Halsey *et al.*, 1995). Over land, evaporative losses will be modified according to changes in vegetative cover. Expected changes include the currently barren High Arctic region being more extensively colonized by tundra vegetation and the gradual shift of the treeline northward on the Arctic mainland. Recent work for the Mackenzie Basin suggests that evapotranspiration will increase for that area (Soulis *et al.*, 1994).

Runoff and Storage

Present Regime

In many permafrost areas, surface runoff is far more important than subsurface flow. For one reason, the presence of relatively impermeable permafrost limits water storage in the ground, except at the southern fringes of the permafrost zone. For another, the presence of seasonally frozen soil restricts infiltration of snow meltwater so that the bulk of spring runoff occurs as overland flow (Woo *et al.*, 1992). This ponding of meltwater combined with accumulated precipitation produces extensive wetland areas which dominate the runoff regime for large parts of the Arctic.

Most rivers in the Arctic exhibit a nival streamflow regime, that is, one characterized by high flows in spring generated by snowmelt and negligible winter flow. In the eastern Arctic Islands, there is frequently a strong glacier meltwater component, while on the mainland there is often a wetland component (flow modified by wetland storages).

Impacts of Climate Change

Under a climate warming scenario, increased precipitation in the Arctic would suggest more water available to generate runoff. Warmer temperatures will, however, both promote increased evapotranspiration and also lead to degradation of permafrost. The latter may be most significant, in that substantial increased sub-surface water storage capacity may result, depending upon the existing degree of ice richness of the permafrost. Consequently, in the thaw season, more water will be stored underground and overland flow will decrease substantially (Woo, 1990). Recent work for the Mackenzie Basin Impact Study indicated that the overall runoff of water from rain or snow which flows into streams, rivers and lakes would drop by 7 percent, although some areas within the Basin could be wetter (Soulis *et al.*, 1994). For the river itself and Great Slave and Great Bear Lakes, levels and flows would be lower during the autumn and winter months and the annual minimum levels would be lower than the extremely low levels observed in 1995. Similar runoff results are also anticipated for the basins of the northward-flowing rivers in the Keewatin-Boothia area to the east.

The nival streamflow regime of Arctic rivers is likely to assume some of the look of a pluvial regime where rainfall events rather than snowmelt dominate (Woo *et al.*, 1992). This is already characteristic of some of the southern margins of the permafrost zone such as the middle Mackenzie Valley, but should become more pronounced there and also extend to other areas of the mainland.

Permafrost

Present Regime

Permafrost underlies as much as 25% of the global land surface. In the Canadian Arctic, it characterizes the entire area with the exception of the land to the south of the treeline in the western Arctic where widespread-discontinuous permafrost occurs, giving way to a scattered-discontinuous character southwest of Great Slave Lake (Figure 27).

In the continuous permafrost zone of the extreme north, permafrost occurs everywhere except beneath newly emerged land or deep water bodies (deeper than 3m) which do not freeze entirely in winter (Woo *et al.*, 1993). Measured depths of permafrost are as much as 600 m along the northern mainland coast (northern Richards Island) and in excess of 500 m on some of the High Arctic Islands. The northerly and southerly boundaries of the discontinuous zone generally follow the 6-8°C and 0°C isotherms respectively of mean annual surface air temperature in Canada. Within this zone, the actual occurrence of permafrost is governed by localized features such as the presence of large water bodies; differing soils, vegetative and snow cover regimes; slope and aspect of the ground; natural ground fires; and human activities.

Ground characterized by permafrost has two features which are of particular immediate concern in regard to the air temperature regime and any change in it. These are the active layer and the presence of ground ice. The active layer is the zone of annual summer thaw over permafrost, a half-metre at most in depth in the northern Canadian Arctic, but increasing to over 1 metre in more southerly areas. Ice in permafrost builds up slowly over an extended period of time (decades to millennia); it can occur in several different forms ranging from pore ice which occupies the pores of rocks and soils, to massive ground ice. The ground ice is usually concentrated in the upper few metres of permafrost, precisely that area of permafrost which would thaw first if air temperature rose. In the Canadian Arctic, permafrost rich in ground ice is most prevalent in the lower Mackenzie Valley area. On Richards Island, for example, typical ice volumes are 60 to 70% at depths of 0.5 to 1.5 m and decline to 40 to 50% at depths exceeding 5 m (Woo *et al.*, 1992).

Recent Trends

A broad correlation is recognized between air temperature and ground temperature in permafrost. Per-

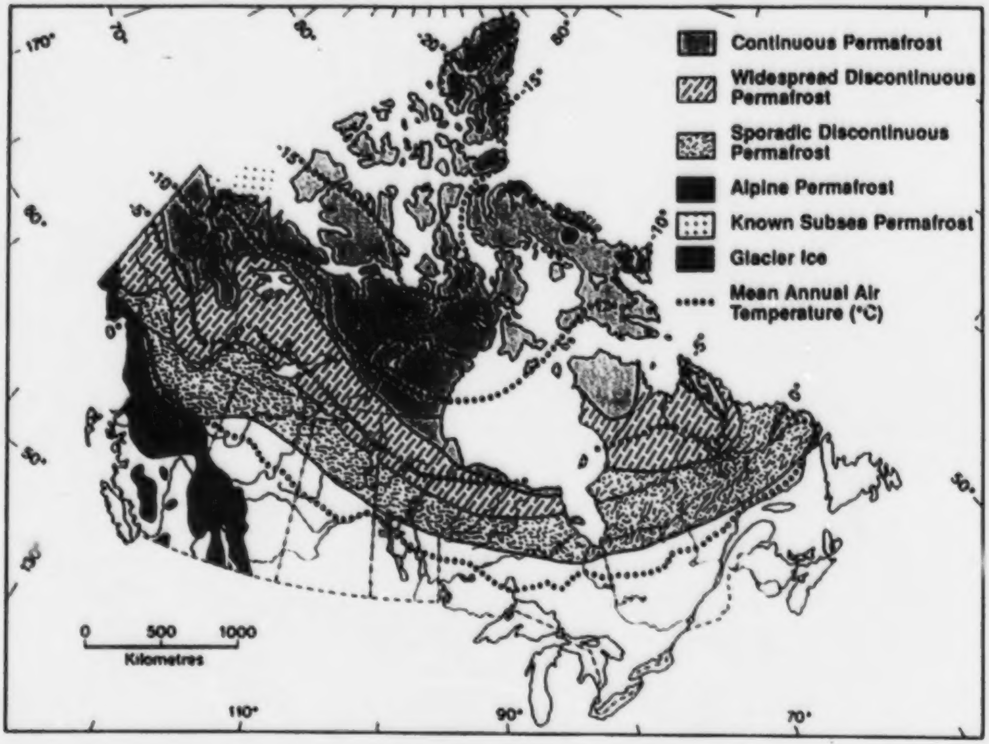


Figure 27. Permafrost distribution (from Prowse and Ommanney, 1990)

haps the most-recognized work on this has involved data from a number of Alaskan sites (Lachenbruch *et al.*, 1988) where increases in near-surface permafrost temperatures of 2 to 4°C have been observed in the last 50 to 100 years.

Both disappearance of permafrost and deepening of the active layer are known to have occurred in the past (Woo *et al.*, 1992). This has been observed as changes in the ice content within sediments that have now refrozen, in the continuous permafrost area on Banks Island and in the discontinuous area in central Yukon, for example.

Shallow landslides can develop in permafrost areas in response to particularly high air temperatures or high precipitation amounts. Such landslides are effectively active-layer failures. They have been of particular interest in the Mackenzie Valley due to their potential hazard to pipelines, although they are known to occur elsewhere in the Canadian Arctic, such as on Fosheim Peninsula, Ellesmere Island (Lewkowicz, 1990). In ice-rich permafrost areas, drought can also trigger landslides; forest fires whose frequency increases during drought can destroy the organic layer and expose the icy sediments leading to such slides. A large fire in 1986 resulted in hundreds of such flows in the Thunder River-Mackenzie River area; many are still active, continuing to deepen into the river banks (Aylsworth and Egginton, 1994).

Along the Beaufort Sea coast, wave action, erosion by sea ice, and thermal degradation have contributed to significant portions of the ice-rich bluffs retreating at rates exceeding 2 m/year. Locally, the rate has exceeded 20 m/year (Harper *et al.*, 1985; Solomon and Covill, 1995).

Thermokarst refers to the terrain which results from processes associated with the thawing of ground ice. In the Canadian Arctic, such thawing has often been due to human activities which strip surface cover from the ground and expose the ice-

Table 2. Response of permafrost to climate warming

Permafrost Feature	Response
Extent	• Responses will vary on both large scales (100s of kilometres) and small (10s to 100s of metres) • Over half the discontinuous zone would disappear eventually • Boundary between continuous and discontinuous permafrost will shift northward by hundreds of kilometers although ultimate position and timing are speculative
Depth	• Active layer deepening slowly in the discontinuous zone to perhaps double its current depth • Ground temperature at depth (30 m) would increase by 1°C
Ice-rich soils	• Tops of ice wedges will degrade • Substantial thaw settlement accompanied by disruption of drainage • Increased likelihood of pronounced thermokarst topography • Increased erosional effects on coasts
Slopes	Increased frequency of occurrence of active-layer detachments (shallow landslides) and retrogressive thaw settlements visually scarring the landscape

rich soil underneath. On Banks Island, ice wedges were exposed when the nearby airstrip was being constructed and their tops subsequently thawed. Irregular hummocks and depressions containing standing water developed, but within 15 years the terrain stabilized although the new surface form will remain indefinitely (Woo *et al.*, 1992). Had massive ground ice bodies been present, much larger thermokarst topography could have resulted, such as the extensive flat-bottomed valleys in parts of northern Russia.

Impacts of Climate Change

The following table summarizes the expected impacts of a climate warming on permafrost in general, taken from Lewkowicz (1992), Woo *et al.* (1992), and EARG (1997). These are based on equilibrium conditions resulting from a warming of 4 to 5°C over 50 years, but it must be remembered that some of the changes in the extent and volume of deep, continuous permafrost will only be attained after a considerably longer time due to the lag time between surface warming and response at depth.

Figure 28 from Woo *et al.* (1992) indicates the likely movement of the southern boundaries of both continuous and discontinuous permafrost across the Canadian Arctic.

More detailed work for the Mackenzie Basin area, conducted for the Mackenzie Basin Impact Study (Dyke *et al.*, 1997), indicated that in the discontinuous zone, the permafrost would become thinner, and disappear altogether in some areas along the southern margin of the region - such as in the Fort Simpson area. In the continuous zone of the lower Mackenzie Valley, the active layer would grow only slightly. Indirect effects resulting from changes in the number of forest fires, heavy rains, or storm surges were not accounted for in this work.

Sea Ice and Icebergs

Sea Ice

Present Regime

The normal sea-ice regime of the Canadian Arctic has been described in some detail by Maxwell (1982).

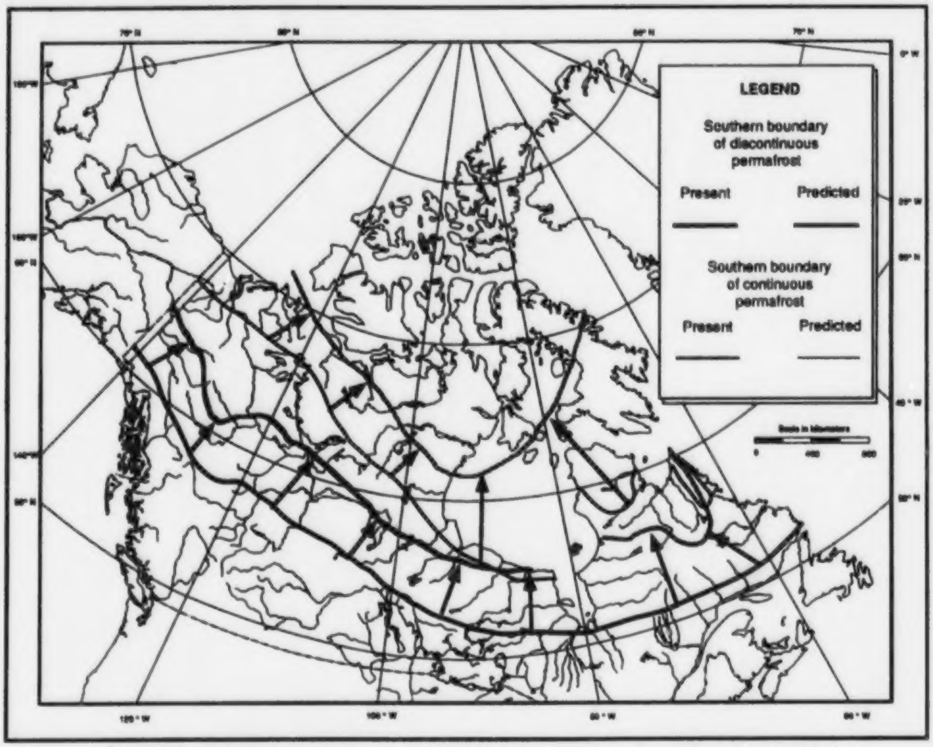

LEGEND
Southern boundary of discontinuous permafrost
Present
Predicted
Southern boundary of continuous permafrost
Present
Predicted
Scale in kilometres
0
400
800

Figure 28. Potential movement of the permafrost boundaries (from Woo *et al.*, 1992)

In the eastern Arctic, where waters are under the Atlantic (Ocean) influence, ice cover characterizes the entire marine area in winter (Figure 29). This ice cover is composed of first-year ice. With the exception of the coastal areas and smaller bays and sounds (such as Jones Sound) where land-fast ice occurs, most waterways are covered with drifting or moving pack ice. Some polynyas (small areas where geography, wind and water current conditions combine to create persistent open water or thin ice) exist - including the 'North Water' at the north end of Baffin Bay, 'Hell Gate' at the western entrance to Jones Sound, and in Foxe Basin to the east of Hall Beach). Only a few areas of the eastern Arctic fail to clear completely of ice by the end of summer (Figure 30). Hudson Bay and Hudson Strait normally do so by mid-to-late August with freeze-up commencing again by early November. Baffin Bay clears from both the north and south starting in late June, leaving its last ice (if any) in the west-central area before freeze-up begins again. Lancaster Sound, the eastern entranceway to the Northwest Passage, normally clears during July, but is then subject to intrusions of floes when adjacent waterways break up.

To the west and north, the marine areas are under the Arctic (Ocean) influence. Ice congestion is normal and complete clearing is unusual; in such circumstances, old ice predominates. This is particularly the case in the northern (among the Queen Elizabeth Islands) and central (around Viscount Melville Sound and M'Clintock Channel) areas. Along the continental coast where fast ice develops during winter from Amundsen Gulf to Spence Bay, summer heating over the tundra to the south and the relatively large size of the adjacent Victoria Island and Boothia Peninsula combine to enable the waterway to clear from west to east in late July and early August. Freeze-up occurs from east to west in late September to early October. The Beaufort Sea ice regime in winter is characterized by predominantly old ice to the north of a line from M'Clure Strait to Barter Island and mainly first-year ice to the south. A polynya off Cape Bathurst in the east expands in June and July allowing exten-

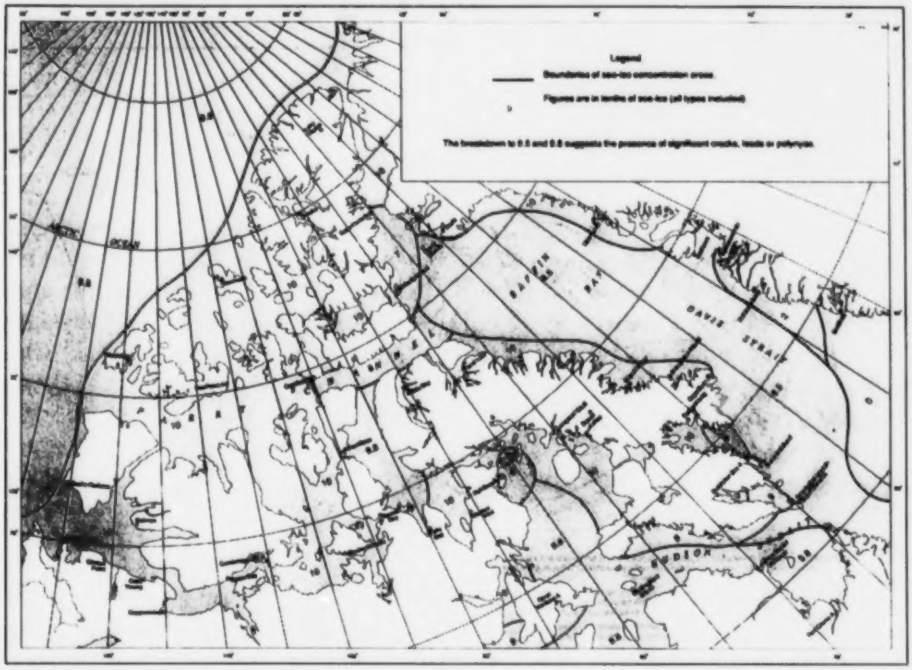

Legend
Boundaries of sea-ice concentration areas
Figures are in tenths of sea-ice (all types included)
The breakdown to 9.5 and 9.8 suggests the presence of significant cracks, leads or polynyas.
ARCTIC OCEAN
BAFFIN BAY
DAVIS STRAIT
HUDSON STRAIT

Figure 29. Mean sea-ice concentration for March 26 (from Maxwell, 1982)

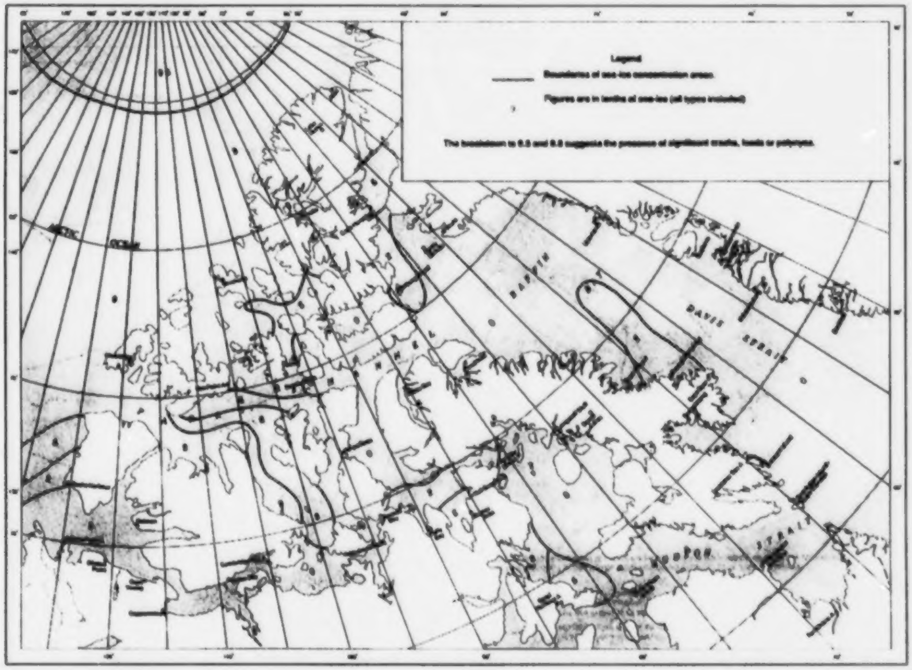

Legend
Boundaries of sea-ice concentration areas
Figures are in tenths of sea-ice (all types included)
The breakdown to 9.5 and 9.8 suggests the presence of significant cracks, leads or polynyas.
ARCTIC OCEAN
BAFFIN
DAVIS STRAIT
HUDSON STRAIT

Figure 30. Mean sea-ice concentration for September 10 (from Maxwell, 1982)

sive clearing of the southern Beaufort Sea unless the polar pack is driven into the area by onshore winds. Freeze-up is relatively late unless old ice is present, taking place in the second half of October.

Figures 31 and 32 show the mean dates of complete freeze-over of marine areas and of water clear of ice in the Canadian Arctic. The former vary from early December in eastern Hudson Strait and central Hudson Bay to early September in the northwestern High Arctic; the latter range from mid-July in northern Baffin Bay and Amundsen Gulf to mid-August in northern Parry Channel. (Of course, some areas in the northwest never clear.)

Figure 33 shows the mean-maximum thickness of first-year ice. The values range from 125 cm in the Davis Strait and southern Hudson Bay areas to double that in the northwestern High Arctic. These values, based on a combination of observed data and theoretically computed numbers, must be used in recognition of the concept that they depict first-year, undisturbed ice growth. Disturbed first-year ice can develop significant ridging characteristics where thicknesses are much greater. Also, it must be realized that thicker, harder old ice predominates in most waterways north and west of Resolute.

Recent Trends

Chapman and Walsh (1993) have looked at the trends in Arctic sea ice extent during the period 1953-1990. They found indications that Arctic sea ice is becoming less extensive during the summer, a decrease that is statistically significant despite the interannual variability in the data. The summer decrease is for the circumarctic as a whole (as determined from the change between the average ice extent for 1961-1975 and that of 1976-1990) and is composed of regional trends around the Arctic varying from large decreases (up to 20%) to no-change to small increases (2 to 3%). In the Canadian Arctic, this overall Arctic summer decrease has been manifest in an increase of 2 to 3% in the Davis Strait-Labrador Sea area, decreases of 2% in Hudson Bay and 3% in the Beaufort Sea, and little change elsewhere. No significant overall Arctic winter trend was found, although sea-ice extent in the eastern Arctic was again found to exhibit an increase (about 8%).

Despite these findings, the IPCC (1995) found little convincing evidence of trends in overall Arctic sea-ice extent although they had low confidence in that conclusion. This is partly due to the limited length of record of sea-ice extent data from satellite observations.

Limited work has been done on trends in ice thickness within the Canadian Arctic. Data from upward sonar profiling by submarine suggests large interannual variability within the Polar Basin, with some evidence of a decline in mean thickness in the late 1980s relative to the late 1970s (Wadhams, 1994; McLaren *et al.*, 1992). Brown and Coté (1992) did evaluate thickness records for land-fast ice but found no evidence of a systematic ice thinning trend in Arctic Canada. Changes in snow cover on the ice was found to be the most important factor in ice-thinning and thickening at two sites (Alert and Resolute).

Impacts of Climate Change

A large change in the extent and thickness of sea ice is anticipated, based on climate projections for the year 2050 (IPCC, 1995). This will result not only from climate warming itself, but also from associated changes in atmospheric and oceanic circulation patterns. There is likely to be substantially less sea ice in the Arctic Ocean. Estimates range from coverage of only 50% of its current area globally (Boer *et al.*, 1992) to 67% of its current area in the Northern Hemisphere (Henderson-Sellers and Hansen, 1995).

For the Canadian Arctic, Wadhams (1990) predicted a decline in Northwest Passage winter fast-ice thickness from 1.8-2.5m at present to 1.4-1.8m and an increase in the ice-free season of 41-100 days. A possible feedback with snow-cover thickness could affect these values, however. Increased snow cover (due to increased storminess) could be sufficiently great that not all ice is melted in summer; then the protection that it offers the ice surface from summer melt could lead to an increase, rather than decrease, in equilibrium ice thickness.

In the coastal zone between the Canadian Arctic Islands and the Arctic Ocean, ice thicknesses are very high (7m or more) with local convergence

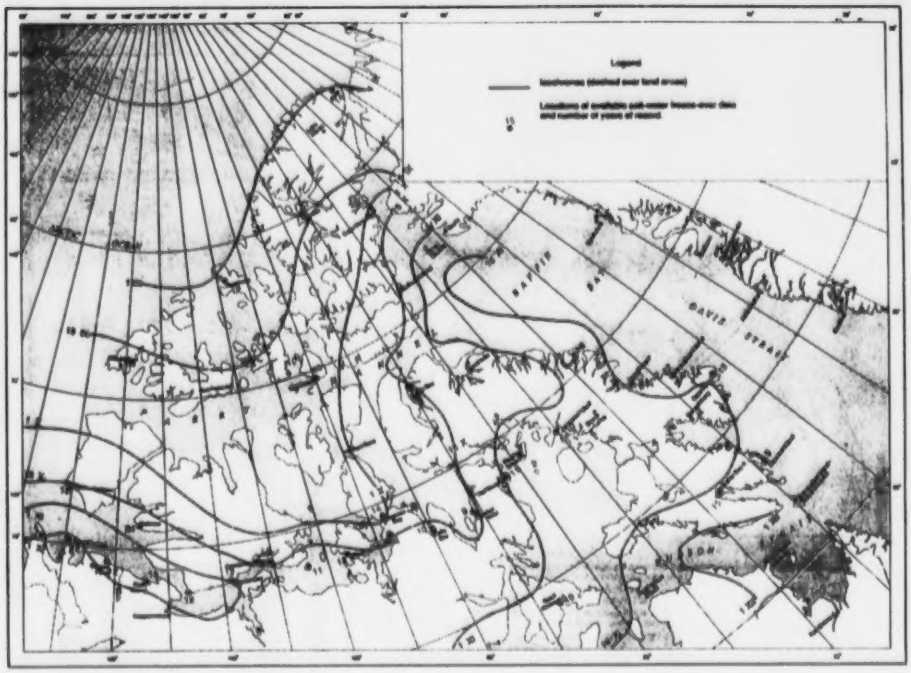

Legend
BAFFIN
BAY
DAVIS
STRAIT

Figure 31. Mean date of the complete freeze-over of salt water (from Maxwell, 1982)

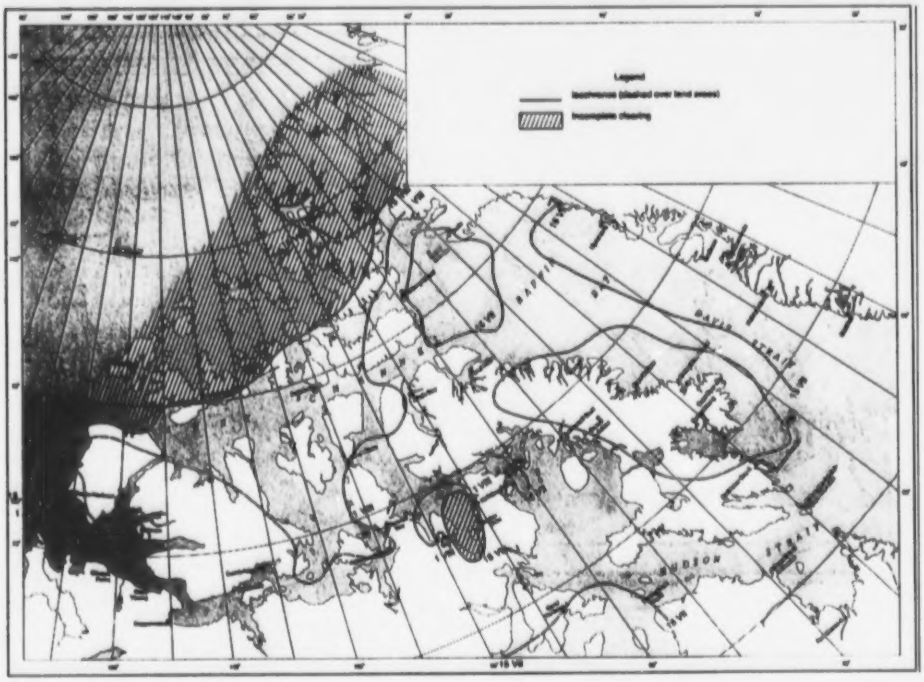

Legend
BAFFIN
BAY
DAVIS
STRAIT
HUDSON
STRAIT

Figure 32. Mean date of salt water clear of ice (from Maxwell, 1982)

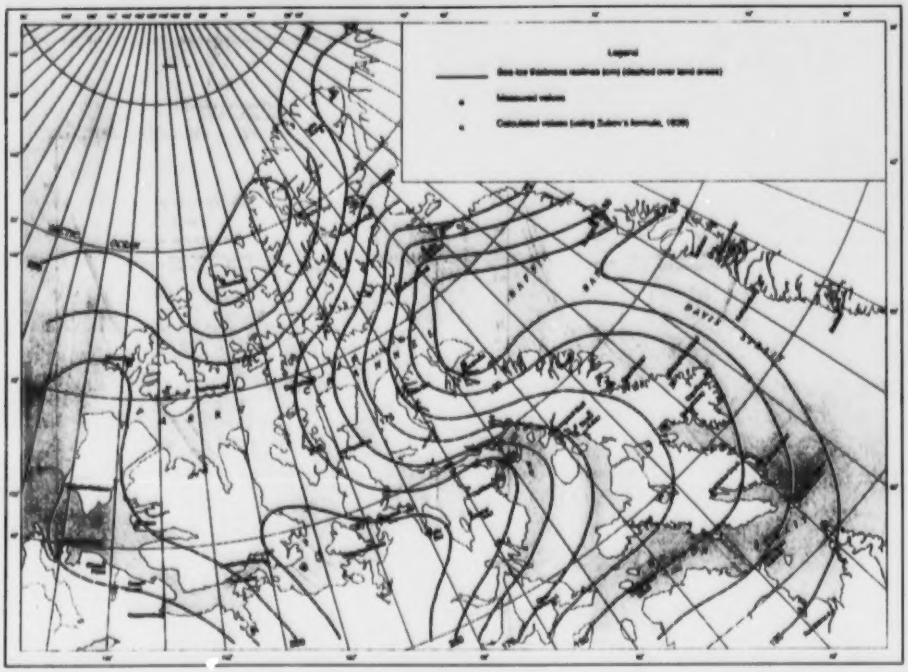

Legend
Sea ice thickness isolines (cm) (dashed over land areas)
Measured values
Calculated values (using Zubov's formula, 1938)
ARCTIC OCEAN
BAFFIN
BAY
DAVIS STRAIT

Figure 33. Mean maximum ice thickness of undisturbed first-year floes (from Maxwell, 1982)

leading to significant ridging. Here, the mean thickness is determined by mechanical factors such as the strength of the ice, and may not be as sensitive to global warming as in other regions (Hibler, 1989).

For the Beaufort Sea area, climate warming would increase the open water season from the current average of 60 days to about 150 days; increase the maximum extent of open water in summer from its present range of 150-200km to 500-800km; and decrease the maximum thickness of first-year ice by 50-75%. Decreased first-year ice ridging thickness and old-ice incursion frequency (given no change in wind regime) are also anticipated (McGillivray *et al.*, 1993).

For Hudson Bay, some GCM results suggest complete sea-ice disappearance in winter (Cohen *et al.*, 1994) while in the Davis Strait- Labrador Sea area, anticipated changes in sea-ice extent and thickness are less clear. At least one GCM suggests increased extent in that area in winter which would be consistent with current trends and suggested indications of cooler temperature in that region under a global warming scenario.

Icebergs

Present Regime and Trends

Icebergs in the Arctic are mainly confined to the Baffin Bay-Davis Strait area and the waterways directly accessing it, such as Jones and Lancaster Sounds. The main sources of icebergs are the tidal glacier fronts of West Greenland and Ellesmere and Devon Islands. A recent estimate suggests total annual production off West Greenland to be approximately 400,000 icebergs. Once calved from the glaciers, icebergs typically take about a year to escape the narrow fjords where they are first formed and the fast ice which restricts their initial movement. Thereafter, they tend to follow paths controlled by regional marine currents (with expected passage times of about 100 days) through Baffin Bay and Davis Strait. Diversions due to groundings in shallow water areas such as near Clyde and Home Bay off eastern Baffin Island often delay passage of the icebergs to Davis Strait well beyond the expected times (up to 15 months and beyond). In general, sea ice is considered to have a dominant role in the timing, release, and deterioration of icebergs moving from the Arctic into the Labrador Sea - Grand Banks areas (Marko *et al.*, 1994).

No reliable information on trends in the number of icebergs calved each year is available. Some work has been done with respect to the numbers surviving to arrive off the east coast - crossing south of 48°N. Analysis for the period 1880-1990 showed no convincing evidence for a systematic improvement in iceberg conditions. Iceberg severity, if anything, appears to mirror recent high levels of sea ice severity off eastern Canada (Marko *et al.*, 1994). This is in accord with lower than average air temperatures that have been observed in the southeastern Arctic.

Impact of Climate Change

Marko *et al.* (1994) suggested that iceberg calving rates would be likely to decrease as glaciers eventually retreated in response to a significant annual warming (+6°C), although short periods of higher calving rates would be possible during the transition period. Glaciers at high latitudes are now, however, expected to change little over the next 100 years (IPCC, 1995), so that iceberg calving rates would also likely change little. Concentrations of icebergs in eastern Arctic waters may therefore remain fairly stable.

Sea Level and Coastal Processes

Both Egginton and Andrews (1989) and Shaw *et al.* (1994) have looked at current sea level in Canada and the sensitivity of the Canadian coastline to sea-level rise, and their work forms the basis of the following two sections.

Present Regime

The Arctic's coastline is 172,950 km in length - 70.9% of the total length of the coastline of Canada - and comprises a wide range of coastal types including deltas, barrier islands, fringing sand beaches, and gravel beaches, as well as unique environments such as ice coasts and breached thaw-lake coasts. In the Arctic, as at any location, relative sea level depends on eustatic conditions (global sea levels) and vertical movement (tectonic adjustments) of the earth's crust. Both emergence (coast rising relative to sea level) and submergence (coast subsiding relative to sea level) are occurring, depending upon the location.

Emergence is mainly the result of isostatic adjustment following deglaciation some 8,000 to 18,000 years ago. The present rate of emergence is a function of:

- thickness and extent of glacial ice,
- earth deformation at and adjacent to the glaciated area,
- time elapsed since the ice load was removed, and
- duration of ice cover.

The areas experiencing emergence include much of the central Arctic and Hudson Bay.

Submergence is due in part to post-glacial subsidence in areas peripheral to the former ice sheet, sediment deposition and loading in large basins, vertical movement of the crust along plate boundaries, and more localized tectonic activity. In the Arctic, submergence is occurring in peripheral regions such as eastern Baffin Island, the northwest fringe of the Arctic Islands, and the Beaufort Sea. A submergence rate of about 0.5m per century for the outermost coast of eastern Baffin Island has been suggested (Andrews, 1989). In the Beaufort region, the rate of relative sea level rise has ranged from 0.1 to 0.4 m per century for the past 3000 years (Hill *et al.*, 1993).

While the Arctic has some coastal processes in common with southern regions of Canada (such as wave action, fluvial and slope processes), others involving sea ice, permafrost, and ground ice are unique to the Arctic. Their relative duration and importance increase or decrease in relation to the severity of the climate. For example, the ability of waves to modify the beach and shoreface is dependent upon the wind regime and the extent and duration of open water. In the Arctic, the existence of sea ice, whose severity in a given year is closely related to climate, is a major determinant of such open-water characteristics.

Impact of Climate Change

One of the main impacts of climate warming is an expected rise of sea level as a result of thermal expansion of the oceans and melting of glaciers and ice sheets. An average increase of about 0.5 m from the present to 2100 is projected (IPCC, 1995).

Overall, much of the Arctic has low sensitivity to such a sea-level change, due to the emergent nature of much of its coastline and the nature of coastal processes occurring. There are important exceptions, however. In particular, the Beaufort Sea region - especially the Mackenzie Delta and Tuktoyaktuk Peninsula areas - will be highly sensitive, as will, although to a somewhat lesser extent, tidewater glacier shores on Devon, Bylot, Baffin and Ellesmere Islands. For the sensitive areas, it may well be that the impact of climate warming on the operative coastal processes will play a bigger role than the sea-level rise itself.

Wave Processes - Longer open water seasons and greater expanses of open water will favour more severe wave development (Solomon *et al.*, 1994). Reduced presence of shorefast ice, grounded ice, or floating sea ice offshore should allow increased effectiveness of waves to rework coastal profiles. Storm surges, which contribute to increased flooding and shoreline erosion (e.g. along the Beaufort coast [Harper *et al.*, 1988; Solomon, 1994]) compared to storms with no surge, are expected to increase in frequency. Coastal areas now protected from wave action by persistent sea ice (such as the low, sand shores of the northwest High Arctic Islands [Taylor and Forbes, 1987]) would be more severely impacted than areas which are seasonally reworked by waves at present.

Sea-Ice Processes - In addition to its role in wave processes, sea ice (and icebergs) also bulldozes, scours, mobilizes, resuspends and rafts sediment. As a consequence, it is responsible for many distinctive features found along Arctic coasts (Forbes and Taylor, 1994). Climate warming will result in thinner, more mobile ice resulting in such impacts as a landward shift in the zone of ice grounding, higher frequency of shore ice ride-up, shallower bulldozing of shore sediment, and a decrease in the height of shore ice pile-ups.

Permafrost, Ground Ice and Glacial Ice Processes - Shores in the Arctic are underlain by discontinuous or continuous permafrost that seasonally melts at the surface. Many sandy shores of the Arctic coastal plain are fringed by a band of bottomfast ice that extends from roughly low tide level to water depths of 2 to 3 m. Coastal areas of Devon, Bylot, Baffin and Ellesmere Islands are characterized by tidewater glaciers. All of these areas are prone to substantial change as climate warming alters, both directly and indirectly, the ice regimes currently existing. For example, a deeper active layer combined with warmer water may lead to more rapid coastal thaw subsidence. More active ground water regimes in the coastal zone will have unknown effects on coastal stability.

Fluvial Processes - In many cases, fluvial processes resulting in large deltas protruding great distances offshore (such as in the Arctic coastal plain) will be disturbed by increased wave action. Greater longshore transport of fluvial deposits and faster resealing of river mouths during low discharge periods will result. Many deltas in this area including the Mackenzie Delta will become more liable to flooding as sea level rises.

Slope Processes - Increased wave action at the base of cliffs and steep shores could trigger increased instability across the upper slopes and the deposition of additional debris in the shore zone. Upper slope failure could occur along the unconsolidated shore bluffs of the eastern Arctic, but even more so along shores composed of ice-rich, fine-grained sediment, as found in the Beaufort Sea area. This leads to more rapid retreat of cliffs and rapid aggradation of spit complexes. Shoaling and other potential navigation hazards would result (Ruz *et al.*, 1992).

Freshwater Ice

Present Regime

Among the Arctic Islands, the freeze-up process on lakes and rivers requires 1 to 2 weeks on the average before completion. Lake freeze-over is complete by early to mid-September north of the Parry Channel, ranging to late October in southern Baffin Island. On the mainland, the dates range from early

October near the Mackenzie coast to mid-to-late November near 60°N. Exceptions are Great Bear and Great Slave Lake which do not freeze over completely until after November 30 and December 15 respectively. River freeze-up is generally delayed by 1 to 2 weeks over that of lakes.

The mean date when lakes clear of ice ranges from May 30 in the southern mainland, to July 1 along the northwestern mainland coast, to July 15 adjacent to western Hudson Bay, to early August over some of the High Arctic Islands. Rivers are about 2 weeks earlier in clearing.

These dates correspond to a lake-ice season lasting from less than 200 days over the southern mainland to 275 to 300 days over much of the Arctic Islands, although in some years, lakes do not clear completely in the latter area. During the season, lake ice thicknesses can grow to as much as about 225 cm (as observed at Alert). Mean maximum ice thickness on the Mackenzie River ranges from 125 to 175 cm, going from Great Slave Lake to the Mackenzie Delta.

Impact of Climate Change

Under conditions of overall annual warming, the duration of river-ice cover would be reduced through a delay in the timing of freeze-up and an advancement of break-up (Gray and Prowse, 1993). This reduction could be up to a month by 2050 (for example, the Mackenzie River - Lonergan and Woo, 1992). The frequency and magnitude of major frazil-ice growth periods could be reduced which would alter the types of ice that make up the freeze-up cover, with implications for hydrotechnical problems associated with particular ice forms (IPCC, 1995).

For Arctic lakes, the duration of ice cover would also be shortened. For example, with an air temperature increase of 4°C, Great Slave Lake could break up 2 weeks earlier (but minimal effect on the date of freeze-up) (Linton and Hall, 1995). A longer open-water period, together with warmer summer conditions, would increase evaporative loss from lakes. Some patchy wetlands and shallow lakes owe their existence to a positive water balance and an impermeable permafrost substrate that inhibits deep percolation. Enhanced evaporation and ground thaw would cause some to disappear (IPCC, 1995).

Terrestrial and Marine Ecological Systems

Sensitivity to Present Climate

In the case of both vegetation and wildlife, habitat is a main driving force which determines what species exist, when and where. The response of vegetation and wildlife species to current climate then is very much an issue of how climate impacts habitat.

For vegetation, assuming appropriate soils exist to allow a given species to take root, climate becomes the determinant through the air temperature, precipitation, and radiation regimes that exist. In the Arctic, there is a vegetation regime which is well adapted to current climate. It is characterized by a treeline extending from near the Mackenzie Delta southeastward across the Keewatin. The treeline is closely related to the position of the 10°C mean July isotherm (see Figure 5c).

Southwest of the treeline, there is a gradual transition from patchy tree growth mainly confined to river banks or sheltered lowlands to the best timber-producing land in the Arctic - the upper Mackenzie area extending from Hay River to the Liard River and along the Mackenzie River downstream to Norman Wells. In this area, species include white spruce and balsam poplar at lower elevations and pine and aspen higher up, with tamarack and black spruce in moist areas.

North of the treeline, very little of the region's soil is capable of supporting large or deeply-rooted vegetation. Low erect growth of woody species such as willow, northern Labrador tea, and dwarf birch, along with diverse heath species, sedges and tussock cotton grass meadows is supported at temperatures down to the 6-8°C mean July isotherm. Further to the north and extending to the 5-6°C isotherm, woody species are prostrate and flowering stalks tend to be shorter on most herbaceous species. At colder mean July temperatures, dwarf willow and sedges persist, but Arctic heather and low growing legumes are local and occur only in the warmest sites, approximately 5°C or more. The 3°C isotherm marks the northernmost limit of most groups. At mean July temperatures less than that, only a small number of herbaceous vascular plant species exist (Edlund, 1986).

Canada's Arctic is rich in wildlife. In the boreal areas of the southwest, caribou (in winter), moose, black bear, wolf, muskrat, lynx, snowshoe hare, beaver and wood bison are found, as are several species of grouse, white pelican, Canada goose and whooping cranes. In the subArctic areas approaching treeline, caribou, moose, grizzly and black bear, polar bear (coastal areas), wolf, beaver, muskrat, red and Arctic fox, and snowshoe hare coexist with spruce grouse, osprey and raven. North of the treeline on the mainland, caribou (summer), grizzly bear, polar bear (coastal), wolf, Arctic fox, and lemming are the main species along with snow goose (nesting and moulting areas) and Canada goose. Further north on the islands, caribou, muskox, polar bear, Arctic fox, and Arctic hare are found along with the snowy owl, snow goose, and gyrfalcon. Marine species there are seal, walrus and whale. Among the high Arctic islands of the northwest are found Arctic hare, Arctic fox, lemming, caribou, polar bear, walrus, bearded seal, rock ptarmigan, and king eider (Environment Canada, 1989).

The cold climate conditions of the region contribute to the relatively slow reproductive and growth rates, slow sexual maturation and long life spans. Plant and animal species diversity and biological productivity are lower than those observed in more temperate regions of Canada.

One result is the presumption that Arctic biota are more vulnerable to the detrimental consequences of environmental contaminants than those of southern areas. Other characteristics of Arctic biota are the simple predator-prey relationships that exist, as reflected by relatively short food chains - for example, the lichen-caribou trophic relationship in the terrestrial ecosystem and the zoo plankton - Arctic cod - ringed seal - polar bear food chain in the marine ecosystem (Environment Canada, 1991).

In the marine environment, the retreat of sea ice in summer is an important determinant of the range of many marine mammals. For example, the bowhead whale's degree of penetration into central High Arctic waters has been shown to have varied considerably over the past 10,500 years in concert with warmer and cooler summer periods (Dyke *et al.*, 1996).

Impacts of Climate Change - Terrestrial

Vegetation - While the direct effects of increased atmospheric CO_2 are generally believed to be beneficial in terms of enhanced and quick-responding plant growth, experimental doubling of CO_2 concentration has relatively little multi-year effect on plant growth in Arctic tundra, presumably because of constraints of low nutrient supply (IPCC, 1995). The indirect impacts are more complex, however.

At the microbial level, all microbiologically-facilitated processes are strongly affected by moisture and temperature. Annual soil respiration rates are likely to increase because of the lengthened season for breakdown of plant material and because increasing temperature strongly stimulates organic matter decomposition, especially in Arctic regions subject to permafrost. At the species level, indirect temperature effects associated with changes in tundra thaw depth, nutrient availability, and vegetation will cause substantial changes in Arctic species composition, litter quality, and nutrient availability. The latter increases shrub abundance and decreases the abundance of mosses, an important soil insulator (IPCC, 1995).

Current global Arctic biomes are eventually expected to change in area as follows: ice - shrink by up to ¼, and tundra and taiga/tundra shrink by up to ⅔ of their present sizes, with the Southern Arctic Ecozone effectively disappearing from the mainland (Neilson and Prentice, 1997). Long-term studies of Arctic tundra ecosystem response to increases in temperatures and snow cover suggest changing ecosystem composition (more shrubs and moisture tolerant vegetation, less nonvascular plants) and decreasing species diversity; recent warm temperatures may already be inducing such changes.

Palaeo studies in the High Arctic have indicated a high degree of adaptability of many tundra ecosystem species to past large changes in climate in high Arctic regions (Hengeveld, 1997 - based on Crawford and Abbott, 1994; Chapin *et al.*, 1995; and Scott and Rouse, 1995). Similarly, palaeo studies near treeline suggest that the response of forest to future climate warming, in terms of radial growth, recruitment and fire frequency, may be relatively rapid (MacDonald *et al.*, 1994). Nevertheless, the very rapid speed at which climate warming is expected to occur, compared to past episodes of climate change, has lead the IPCC (1995) to conclude that the speed at which forest species grow, reproduce, and re-establish themselves or that appropriate soils can be developed will be outstripped.

The shrinking of the Arctic tundra biome will occur hand-in-hand with a northward shift of the treeline, by up to 750 km in eastern Keewatin (Rizzo and Wiken, 1992). The species composition of forests is likely to change; entire forest types may disappear, while new assemblages of species, hence new ecosystems may be established. An increased incidence of forest fires is likely, such as already observed in Alaska (IPCC, 1995).

This increase in forest fires, along with more insects and a longer growing season, is expected to result in noticeable changes in vegetation in the Mackenzie Basin. For areas of commercial timber in the Basin, without changes in fire management, the number of forest fires in the area would increase and the average number of hectares burned annually would double. Even though the rate of growth of hardwood trees would improve, a larger percentage of softwood trees would die each year as the direct result of a warmer climate. With the fire scenario factored in, the average age of trees will decline and the yields from all stands of commercial timber - both softwood and hardwood - will fall by 50% (Hartley and Marshall, 1997; Kadonaga, 1997).

Insects now common to southern Canada would move into the Mackenzie Basin area. Similarly the pests which are in the region today would move not only further north but also to higher elevations. According to one warming scenario, the number of hectares which would become susceptible to the white pine weevil would more than double to include all the forested area. (The weevil, a southern pest at present, slows down forest regeneration.) (Sieben *et al.*, 1997)

Scenarios for 2020 and 2050 for areas of boreal and subarctic peatlands project a temperature increase of 1 to 2°C and a decrease in soil moisture. Peatlands will be extremely vulnerable to climate change if warmer temperatures lead to thawing of the permafrost layer and affect their hydrology through changes in surface elevation, drainage, or flooding. It is likely that they would switch from a carbon sink to a carbon source (Oechel *et al.*, 1993). These wetlands have a limited capacity to adapt to climate change because it is unlikely that new permafrost areas will form and permafrost is a key factor (along with lack of hydraulic gradient) in maintaining high water tables in these peatlands (IPCC, 1995).

Wildlife - While the direct effects of climate warming as manifest in a changing of the thermal stress on animals is an important consideration, in the Arctic it is the indirect effects of global warming on food and water availability that will be the more significant (Mathison and Christopherson, 1994). Changes in timing and abundance of forage availability and parasite infestations may combine to drive populations into decline with serious consequences for people still depending on them (Jefferies *et al.*, 1992).

Caribou are a widely-present species throughout much of the Canadian Arctic. They are greatly dependent upon access to tundra vegetation such as lichen for forage and so increased or more-heavily-encrusted snow cover can put such vegetation beyond their reach. Muskoxen are similarly dependent and affected. In the Mackenzie Basin, the effect on caribou would be pronounced. The Bathurst herd which lives north of Great Slave Lake would probably lose weight in part due to heavier snow cover, and in part due to an increase in the number of insects harassing the herd (Brotton and Wall, 1997). The northward shift of the treeline would increase competition among the mainland barren-ground caribou herds for preferred calving territory, with potential negative consequences for herd populations (Environment Canada, 1991). North of the mainland, High Arctic Peary caribou and muskoxen may become extinct. Arctic Island caribou migrate seasonally across the sea ice between many of the Arctic Islands in late spring and fall. Changes in sea ice would disrupt those migrations with unforeseen consequences to population survival and gene flow (Gunn, 1995).

Similarly, other high Arctic Island animals such as Arctic fox and wolves would be limited in their inter-island movements thereby reducing their opportunity to find suitable habitat and new sources of food (Environment Canada, 1991). In the Mackenzie Basin, fur-bearing animals might be affected by a rise in the number of forest fires. Lynx and marten may decline while red fox may benefit (Latour and Maclean, 1997). Reduced muskrat populations are already apparent in the southwestern NWT due to lower water levels in the Peace-Athabaska Delta (Cohen, 1997a).

Throughout the Arctic, predator-prey relations are a critical component of life cycles of Arctic species. Such relations will shift where snow cover and snow type distributions change. For example, wolves flounder in deep snow that caribou can cross, but can follow moose which are no better suited to travel through soft snow (Telfer and Kelsall, 1984).

In general, the Arctic is a primary western hemisphere breeding and moulting ground for shorebirds and waterfowl, and in some areas of the Canadian Arctic, their low-lying coastal habitat could be affected by permafrost degradation and sea-level rise, which would lead to salt water intrusion (Environment Canada, 1991). Recent work for the Mackenzie Basin Impact Study has, however, suggested that the summer habitat of shorebirds in the Mackenzie Delta probably would not change much (Gratto-Trevor, 1997). In the northern Mackenzie Basin, warmer spring and summer temperatures would be favourable for Arctic-nesting geese, but permafrost thaw and increased fire frequency would damage habitat. On balance, projected future changes in climate and environmental conditions are more likely to be detrimental than beneficial to geese (Maarouf and Boyd, 1997). Boyd (1988) earlier found that spring conditions of low temperatures and late snow cover are associated with poor breeding success for Arctic goose populations, but that above average spring temperatures or earlier snow cover clearance (both characteristics of climate warming) are somewhat, but not strongly, linked to good breeding success.

Migrating Arctic birds may be impacted by changes in areas outside the Arctic upon which they are dependent, e.g., Arctic-nesting geese lay down fat stores for breeding in the Arctic by feeding on grains in the Canadian prairies and northern United States (Diamond, 1998). Thus, altered conditions in such locations could have a detrimental effect regardless of changes in the Arctic.

Impacts of Climate Change - Freshwater and Marine

Lake temperatures would rise but the effect on fish habitats in freshwater is uncertain. Cold water species might be at greater risk as their potential to adapt is not completely known. Arctic char, for example, is one species which could be affected as the northward expansion of southern fish species, such as brook trout, provides competition (Environment Canada, 1991; Cohen, 1997a). The IPCC (1995) has estimated that many species in lakes and streams are likely to shift poleward by about 150 km for every 1°C increase in air temperature. This axiom may also be useful for estimating oceanic impacts, at the general level.

At high latitudes where the range of temperatures found in the ocean is small (-2 to +3°C), small changes in water temperature could have pronounced effects on biological rates of growth and development. There, the seasonal development and regression of sea ice is of substantial biological importance. Warming, changes in upwellings, circulation variations, and wind changes would affect the distribution and characteristics of polynyas (ice-free areas, such as the North Water at the northern end of Baffin Island, Hell Gate between Devon and Ellesmere Islands, in Foxe Basin off the coast from Hall Beach, and in Penny Strait) and ice edges that are vital to Arctic marine ecosystems. Areal centres of food production will almost certainly shift as underlying primary productivity changes due to alterations in upwelling, loss of ice-edge effects, and ocean temperatures. Changes in critical habitats such as sea ice (as it thins and retreats due to climate warming) and nesting and rearing beaches (due to sea-level rise) will occur (IPCC, 1995).

In the Beaufort Sea, large-scale coastal circulation is dependent in part on brine rejection during freezing of sea ice and under-ice topography (pressure ridging). Both of these forcing variables will change, possibly substantially, as a result of changing sea-ice development. Thinner sea ice means less brine formation which will affect the strength of the circulation and probably its timing as well. Changes in sea-ice thickness will also affect the location and intensity of pressure ridge development. The effects on biological productivity are not known, but may be significant (MacDonald and Carmack, 1991; MacDonald *et al.*, 1995).

At present, it is difficult to predict the magnitude and significance of climate change impacts on mammals such as polar bears, whales and seals, or on seabirds. They may be both positive and negative, even on the same species. Positive effects such as extended feeding areas and seasons, more productive high latitudes, and lower winter mortality may be offset by negative factors that alter established reproductive patterns, breeding habitat, disease vectors, migration routes, and ecosystem relationships (IPCC, 1995).

The range and numbers of some Arctic marine mammals, such as beluga and bowhead whales, may increase (Environment Canada, 1991) or at worst hold steady. Many such mammals are able to locate and follow seasonal centres of food production as well as altering their migration routes to accommodate interannual differences in environmental conditions (IPCC, 1995), so they may be able to adapt to altered conditions under climate warming.

Ringed and bearded seals, sea lions and walruses require expanses of ice cover for breeding, feeding and other habitat functions and may suffer population decline through pack ice recession. Some stocks have life histories that tie them to specific geographic features (pupping beaches, or ice fields as habitats and locations of prey species), in which case they may be more severely impacted if such features disappear or move elsewhere. Reduced habitat possibilities will also increase such species' vulnerability to natural predators and human hunters and poachers. On the other hand, some species (e.g., the sea otter) could benefit by moving into new territories with reduced sea ice (Environment Canada, 1991; IPCC, 1995).

The consequences for polar bears may be especially of concern because climate warming will affect not only biological productivity of the marine ecosystem and the distribution and abundance of the seals they depend on for food, but also the sea-ice surface that provides the essential platform upon which they hunt and whose maximum seasonal surface area determines the extent of the polar bear's habitat. First impacts will be felt in the James and Hudson Bays where the whole population is already forced to fast for about 4 months when the sea ice melts in summer. Prolonging the ice-free period will increase nutritional stress on this population until they are no longer able to store enough fat to survive. Early signs of impact will include declining body condition, lowered reproductive rates, reduced survival of cubs, and an increase in polar bear-human interactions (most of which are already detectable). In the High Arctic, a decrease in ice cover may stimulate an initial increase in biological productivity; eventually, however, it is likely that seal numbers will decline if the quality and availability of breeding habitat is reduced. Should the Arctic Ocean become seasonally ice-free for a long period, it is likely that polar bears would become extinct (Stirling and Derocher, 1994)

Small aquatic furbearers (muskrats, beavers, mink) will face ecosystem alterations that will change their abundance and distribution (IPCC, 1995), but no further detail is known.

The distribution of seabird breeding colonies in the Arctic is closely tied to polynyas and coasts where the sea ice breaks up early - southwest Greenland, Hudson Strait, and the North Water polynya at the north end of Baffin Bay, for example. Global warming is likely to benefit these seabirds by melting sea ice earlier, giving the birds access to feeding areas; by extending the growing period for phytoplankton and thus for the whole very short marine Arctic food cycle; and by the earlier melting of snow which will give birds nesting on cliff ledges and in boulder sprees earlier access to nest sites (Brown, 1991). If, however, warming proceeds to the point of severely reducing the extent of sea ice, overall food supplies may decline, as much of the Arctic food web depends on algae living under the ice (Diamond, 1998).

Table 3. Oil and gas wells drilled in the Canadian Arctic

Region	Wells Drilled	'Significant' Discoveries
Beaufort Sea/Mackenzie Delta	100+	35
Arctic Islands	170	18+
Hudson Bay	5	0
Total	275+	53+

Socio-Economic Sectors

Climate change impacts and adaptation are summarized for a number of socio-economic sectors important in the Arctic. The amount of detail presented for each is generally reflective of the volume of literature rather than the relative importance of the sector in the region's economy. Some important economic sectors (for example, mining, finance and insurance) are not treated separately because little or no work has been done on impacts with respect to them for the Arctic. Where appropriate, reference to them is included in the sections on other socio-economic sectors or aspects of the physical environment.

Oil and Gas

History and Sensitivity to Climate

In Arctic Canada, areas with potential for oil and gas were first offered for lease by the federal government in the 1960s. Subsequently, such leases were taken up by numerous petroleum companies and coverage extended over the Mackenzie Valley and Delta area and virtually the entire offshore - Davis Strait and Baffin Bay; Hudson Bay, Foxe Basin and Hudson Strait; Parry Channel (Lancaster Sound and Barrow Strait); Beaufort Sea; and the Queen Elizabeth Islands (both waterways and islands). A large number of wells were drilled in these areas mainly during the 1970s and early 1980s. Table 3 shows the results of the drilling activity. (Note that 'significant' discoveries are not necessarily commercial.) As a consequence of the relative success of drilling in the Beaufort Sea and Mackenzie region, most of the more recent interest has focused on those areas.

Petroleum operations range from exploration to production to transportation, including any associated construction activities - and all are affected by climate conditions. The climate and related variables of concern for onshore operations are: air temperature; precipitation; wind speed and direction; permafrost depth, extent and degree of ice richness; snow cover depth, extent, and length of season; reduced visibility events; and river flow regime. For the offshore, to these may be added: sea-ice age, thickness, concentration and movement; iceberg size, frequency and movement; wave height and period; structural icing potential (function of temperature, wind speed and wave height); sea level; storm frequency and severity; coastal erosion; and river discharge. Examples of sensitivity are given in Table 4.

Adaptation to Present Climate

In conventional offshore regions of the world, where the presence of ice is not a concern, exploratory drilling is carried out either from drilling vessels or from temporary fixed platforms such as jack-ups or grounded barges. Such systems fit the basic needs of offshore drilling which include having a stationary platform relative to a point on the sea floor and a 60-100 day window for drilling and testing a well. In the offshore Canadian Arctic, for example in the Beaufort Sea, conventional offshore systems are quite unsuitable due to the presence of an ice cover for at least 9 months of the year, the variability in the open-water season, and the potential for polar pack ice to invade the open-water region at any time (Croasdale, 1993). In the eastern Canadian Arctic, an additional concern is the presence of icebergs.

In order to adapt to such conditions, the oil and gas industry responded with new technology and operating techniques tailored specifically for dealing with ice. In some operations, the ice was

Table 4. Sensitivity of oil and gas operations to climate

Climate and Related Variables	Examples of Oil and Gas Operations Sensitivity
Air Temperature	• Steel selection for drill platforms and pipelines • Engine efficiency of construction and maintenance vehicles • Design and operation of compressor operations • Role in design of offshore platforms for structural icing potential
Wind	• Design of offshore structures for extreme wind speed • Role in design for wave height, structural icing, and sea-ice movement • Frequency of reduced-visibility events
Precipitation	• Effect on construction timetables • Contribution to river flow regime • Role in design for structural icing
Snow Cover	• Design of land-based construction activities for exploration support, production facilities and pipelines • Continuing access to land facilities for maintenance (eg. winter snow roads)
Permafrost	• Design and construction of coastal and inland facilities • Continuing access to land facilities
Sea Ice	• Design and operation of offshore and coastal-support facilities • Design of marine transport systems
Visibility	Air and rotary-wing support to construction, operations and maintenance
Storms	Design and operation of offshore platforms and support facilities
Icebergs	• Design and operation of offshore platforms and support facilities • Design and operation of sea-bed pipelines
Waves	Design and operation of offshore platforms and support facilities
Sea Level	• Design of offshore platforms • Design of coastal facilities
River Regime	• Design of coastal facilities • Pipeline routing and construction • Continuing access to land facilities

avoided; in others, structures were designed to resist the ice; and in some instances, the ice itself was strengthened and used to drill from. In the eastern Arctic, the preferred approach has been to avoid the ice by using ice-strengthened drillships, which are capable of disengaging from the well and moving off-site when threatened by ice floes or icebergs. Operations have been confined to the open-water season of approximately July to October. In the northern Arctic, amongst the Arctic islands, use of the ice itself as a platform has been favoured. The technique involves locally thickening landfast ice (by flooding it) and then placing a drill rig on it. Drilling is conducted during the winter, from approximately January to May. In the Beaufort Sea area, both the drillship and strengthened ice techniques have been used - the former in the deeper waters and sometimes assisted by icebreakers to help extend the drilling season in the fall, and the latter in shallower waters. Additionally, the concept of artificial islands was introduced for shallow waters (<19m). This involved the construction of islands by dredges using local sand and the employment of sand bags for slope protection. The concept was extended to somewhat deeper waters (<30m) by using caissons as retaining walls.

Despite the general success of these various approaches in allowing drilling in the Canadian Arctic offshore to be undertaken, the constraints imposed by ice in terms of lengthened construction times, abbreviated drilling seasons, and enforced idleness of drilling equipment and support vehicles has resulted in very high costs. For example, exploratory wells in the Beaufort Sea have cost as much as $100 million whereas, in a conventional offshore area, a well cost of greater than about $20 million would be unusual (Croasdale, 1993).

Impacts of Climate Change

In general, offshore operations should become easier and less costly, due to a decrease in the thickness and incursion of first-year and multi-year ice and an increase in the open water. **Exploration** - With lengthier open-water seasons, wells should be able to be drilled and tested in one season. For exploratory drilling using drillships, costs could be reduced by at least 30% and possibly 50% (Croasdale, 1993). Balancing this somewhat is the view that increased wave height and period, an increase in sea level and increased coastal erosion and storm surges would have negative impacts on offshore operations by pushing up design requirements for offshore structures and associated coastal facilities (McGillivray *et al.*, 1993; Anderson and DiFrancesco, 1997). **Production** - Although ice concerns will be reduced, the presence of some ice will still prevent the use of conventional offshore technology. Design ice loads should be reduced, however, to about 60% of the current value which would result in important cost savings. Similarly, significant savings in construction costs, perhaps 30-50%, should be realized. This would be especially true for offshore pipelines which require a trench to protect against ice scour, although increased trenching or tunnelling at landfall sites may be needed due to coastal instability. **Transportation** - The high cost of transportation is a significant barrier to the economic production of oil and gas in the Beaufort Sea area. Oil and gas pipelines to the south are unlikely to be less expensive as their design would have to recognize increased permafrost instability. On the other hand, the use of ice-breaking tankers should be more efficient and less costly (Croasdale, 1993).

Onshore oil and gas activity is very closely tied to design needs for meeting permafrost characteristics and coastal conditions. Climate change suggests that both of these areas will experience significant impact - increased instability of permafrost, and increased flooding and erosional concerns in coastal areas. Thus there could be significant design concerns and cost implications for onshore operations.

In practice, the uncertainties in climate scenarios are such that the oil and gas industry cannot incorporate the positive impacts of climate change into current design. Negative impacts, however, would be considered because of the conservative approach adopted by industry. As a result, then, at present, climate change is generally viewed to cause an increase in cost for operations in the Canadian Arctic.

Adaptation to Climate Change

- Altered design practices for all phases of activity: type of materials; wind, wave and ice loading capacity; sea-level-sensitive structures; routing and siting
- For offshore activities, replace the use of ice roads for supply and construction and ice platforms for drilling with marine systems

Transportation

Background and Sensitivity to Climate

The mix of transportation in Arctic Canada includes all the major modes of air, marine, freshwater, and land transportation.

Air transport provides the major means of movement of people (and to a lesser extent freight) to and between distant locations in Arctic Canada. All regions are serviced by major commercial carriers, with the major centres being Yellowknife and Inuvik in the Mackenzie area, Resolute and Rankin in the central Arctic, and Iqaluit in the east. North-south connections are more readily available than are east-west. Smaller carriers operate locally, with both fixed- and rotary-wing aircraft available. Such carriers are often employed for logistical support to exploratory, research, and tourism activities. Military air transport services Alert in the High Arctic.

Marine transport is an important activity in the eastern Arctic during the open-water season when major resupply trips are undertaken from eastern ports in southern Canada. Such resupply has extended into the islands of the High Arctic in the past. In the same region, important zinc/lead mines at Nanisivik and on Little Cornwallis Island depend on marine transport to take ore southward in the summer. Grain shipment from Churchill across Hudson Bay and through Hudson Strait to southern markets is also carried out during that season. In the western Arctic, marine transport has provided logistical support for offshore oil and gas exploration in the Beaufort Sea during the open water season. The potential for marine transport to bring oil or liquid natural gas out of the Arctic has been of great interest ever since the initial discoveries in the Beaufort and among the High Arctic Islands in the 1970s.

In the Mackenzie area, freshwater transport by barge along the Mackenzie River is a vital activity during the ice-free season, providing important movement of fuel, bulk goods and general commodities. Ferry service on the Mackenzie is also an issue.

Land transport is a major concern in the Mackenzie area. Included are rail transport into Hay River from the south, permanent roads in the southern portion of the region, winter roads (from early January to the end of March) including a major one down the Mackenzie Valley from Fort Simpson to Norman Wells, and ice roads in the southern Beaufort which have been used by oil companies to transport equipment to drill sites.

Table 5 identifies the major climate and related variables which may effect transportation in the Arctic.

Adaptation to Current Climate

Air: Runway construction through selection of materials and construction techniques has been a major area of adaptation for air transport in the North in order to minimize damage arising from disturbed permafrost. Smaller planes in some instances use skis for landing on ice or snow runways in winter, where they would normally use wheels or floats. Navigation aids have been developed in order to assist operations under adverse weather conditions.

Marine: The first method of adaptation has been to avoid ice, thus restricting shipping to the open-water season. Where attempts have been made to ship through ice-infested waters, ships have been either been strengthened to withstand ice using different bow designs, thicker steel plate, and different steel alloys, or have been accompanied by icebreakers. Ice reconnaissance and forecast systems have been developed to aid in avoiding dangerous ice conditions.

Freshwater: Ice-season alternatives such as winter roads have been developed.

Land: Design and construction of road and rail beds have been adapted to permafrost and the pattern of freeze-thaw cycles found in the North. Winter roads are constructed and are designed to protect the natural environment over which they pass and utilize ice-covered rivers lakes and streams wherever possible to minimize costs and provide a naturally-level surface.

Impacts of Climate Change

The most significant change in transportation demand would result from the northward expansion of agricultural, forestry and mining activities in Canada. While much of this will be reflected in increased population and intensified settlement pat-

Table 5. Climate and related variables affecting Arctic transportation

Transport Mode	Climate Variables
Air	• Ceiling and visibility • Wind speed and direction • Storm occurrence • Permafrost, ice and snow cover (runways) • Open-water season (floatplanes)
Marine	• Sea-ice concentration, floe size, age, ridging • Iceberg occurrence, movement • Wave height and period • Wind speed and direction • Air temperature • Sea-level height • Storm frequency, severity
Freshwater	• River and lake ice: freeze-up and break-up dates, length of season, thickness • Precipitation
Land	• Air temperature • Precipitation • Visibility • Ice on rivers and lakes • Snow cover thickness, length of season • Permafrost characteristics

terns in Canada's central regions (IBI Group, 1990), the Arctic seems likely to be affected too, particularly in the southern Mackenzie area. The result of such movement would be the need for expanded air, marine, rail, and road coverage and related facilities.

In terms of existing transportation, a mixture of benefits and detriments is expected.

Air: Warmer, less dense air would result in reduced lift thus reducing allowable payloads in general. Float planes would benefit from a longer ice-free season, but there would be a correspondingly shorter season for winter ice strips. An increased frequency of storms and therefore reduced-visibility events could lead to more downtime and/or increased costs for improved navigation aids (IBI Group, 1990).

Marine: The impacts in Arctic areas would likely be significant (Maxwell and Barrie, 1989). Benefits would take the form of longer shipping seasons in all Canadian Arctic areas with the likelihood of easy transit through the Northwest Passage for at least part of the year, deeper drafts in harbours and channels, and the potential for reduced need for strengthening of hulls to counter ice conditions and/or reduced need for icebreaker support. On the other hand, increased costs would result from design needs to address greater wave heights, possible flooding of coastal facilities in the Beaufort Sea and Hudson Bay, and the generally increased need for navigational aids owing to increased precipitation and storm frequencies and requirements for search and rescue activities. An increased sediment transport regime is likely to require more frequent surveys to monitor local shoaling.

Freshwater: The length of the Mackenzie River barge season would increase, perhaps by as much as 40% (Lonergan and Woo, 1992), but lower water levels would make navigation more difficult (Cohen, 1997a).

Land: Increased permafrost instability will likely lead to increased maintenance costs for existing all-weather roads and rail beds, at least in the short term. The season for winter roads will be both shorter on average and more uncertain owing to altered ice regimes of the many rivers, streams, and lakes that such roads often cross.

Adaptation to Climate Change

- Altered design practices for each transportation mode to account for changed climate regime
- Changed mix of transport modes depending upon the region of the Arctic

Building and Construction

Background and Sensitivity to Climate

Building and construction in the Arctic involves a wide range of concerns: buildings in towns and cities; sewage and utility corridors; dykes and dams; road, bridge and airstrip construction; mining structures and tailings ponds; pipeline construction; coastal structures for marine activities; and offshore drilling platforms. Some of these are dealt with in other sections (for example, pipeline construction and drilling platforms are considered under 'oil and gas', while road construction relates to 'transportation'). In general, the main concern for northern construction is permafrost which underlies the entire area either in continuous or discontinuous form (see 'permafrost' section). Factors guiding engineering practice for northern building and construction include:

- permafrost extent and depth, ice richness (pile and foundation design)
- thickness of the active layer (pile and foundation design, construction access)
- air temperature (building material, insulation need)
- wind load and snow load (structural integrity)
- wind direction and snow cover (building orientation, construction access
- solar radiation (materials subject to UV degradation)

It is important to bear in mind that the impact on the ground temperature due to construction itself is very critical in permafrost areas. This can cause significant and progressive permafrost thawing which results in surface settlements and eventual distress to the structure. Roads and airfields are the facilities in the Arctic which cover the largest areas and therefore encounter the most problems. Paved and plowed roads and airfield surfaces commonly increase the mean annual surface temperature by 1 to 2°C over the original undisturbed condition. By comparison, those facilities which are allowed to remain snow-covered in winter, such as gravel pads, embankment slopes, dykes, and dams have been noted to have mean surface temperature increases of 3 to 6°C, depending upon the solar exposure. Building and bridge foundations can have extremely variable surface temperature effects, ranging from the net cooling effect of areas shielded from sunlight and snow cover but open to winter air circulation, to strong net warming beneath the floors of heated buildings (Esch, 1993).

Adaptation to Present Conditions

- Use of design values developed from studies of climatic data, often embodied by building codes. Safety factors are usually built into the design values to allow for risks related to variability in the climate data.
- Development of specific combinations and thicknesses of materials for use in building pads or runway and pipeline bases to reduce conduction of heat to frozen ground below
- Ventilated basements or ventilation ducts in the ground under the floors of buildings, or use of thermosyphons and thermal piles
- Development of above-ground utilidors for power, sewage lines
- Concept of the igloo

Impacts of Climate Change

Increased air temperature will have a number of effects including: reduced power demand for heating, reduced insulation needs, and increased length of the season for construction activities that occur in summer (heavy construction, which may be confined to winter due to the movement of equipment only being possible on frozen, snow-covered ground, would face a shorter season). In

Table 6. Limiting climate factors for recreation and tourism

Aspect		Limiting Climate Factors
Regional Access	Air	Occurrence of very low cloud and/or visibility (300 m and/or 5 km ranging down to 60 m and/or 0.8 km, depending upon the type of aircraft and airfield))
	Water	Length of shipping season as defined by break-up and freeze-up dates (Mackenzie River, Hudson Strait into Hudson Bay, Davis Strait into Baffin Bay and Parry Channel)
	Land	• Break-up and freeze-up periods when ferries or ice bridges linking highway routes across rivers are inoperable • Thickness and stability of ice in winter, for winter roads
Local Access	Air	• Occurrence of low cloud and visibility • Snow cover and ice thickness/uniformity for winter landing sites • Dates of spring-summer and fall-winter transition periods
	Water	• Break-up and freeze-up dates • Strong winds, particularly squally winds
	Land	• Snow cover, wind chill and poor visibility in winter • Length of thaw season and changes in active layer
Activity Itself	Winter	• Length of daylight and amount of twilight • Temperature and wind chill • Visibility • Arctic white-out
	Summer	• Temperature • Visibility • Winds • Thunderstorms (lesser importance)

from: Crowe (1976)

addition, it has implications for changes in freeze-thaw frequency and on permafrost extent (reduced in area) and active layer depth (increased). Nixon *et al.* (1990) and Nixon (1994), as summarized in EARG (1997), identified a number of specific concerns.

- Northern pipeline design: Increased frost heave and thaw settlement. Slope stability in discontinuous permafrost will also be an issue. Increased fire occurrence will result in more frequent active layer detachment slides, and decreases in permafrost thickness will make large rotational failure more likely, particularly along high river banks.
- Pile foundations in permafrost: The settlement of shallower pile foundations could be accelerated by climate warming over the design life of a structure, say 20 years. Deeper piles for heavier structures, however, would be less affected in the same time period.
- Tailings disposal facilities: Might be affected (negatively or positively) by climate warming, due to the long-term effects on frozen or unfrozen tailings. Layers that freeze during winter disposal may thaw out many years later, releasing excess water and contaminants into the ground. Climate warming could play a significant role in the rate of melting of such materials.
- Bridges, pipeline river crossings, dykes, and ero-

sion protection structures: Precipitation changes and changes to soil permeability would alter run-off patterns, and possibly the ice-water balance in the surface active layer. It would be very difficult to assess the effects of these changes on engineering structures.

- Open pit mine wall stability: May be affected where steep slopes in permafrost overburden have been exposed for long periods of time. The engineering issues would revolve around deepening thaw, with consequent increased pore pressures in the soil/rock, and resulting loss of strength and reduction in pit wall stability.

Recreation and Tourism

Present Climate Regime

Outdoor recreation and tourism, important contributors to the northern economy, are highly climate-sensitive activities in the Arctic. Activities are diverse, including: hunting (caribou, polar bear, muskox), fishing (Arctic char, trout, grayling), hiking, camping, rafting, touring (automobile - only in the western Arctic, dogteam/sled, seagoing launch), canoeing, kayaking, mountain climbing, naturalist opportunities, and historic and archaeological tours. For many, the region's parks (Nahanni, Wood Buffalo, Auyuittuq, and Ellesmere Island National Parks, not to mention numerous territorial parks), historic sites (Kekerten, Qaummaarviit, and Northwest Passage Historic Parks), game sanctuaries (Thelon Game Sanctuary), and wilderness hiking (Canol Heritage Trail from Norman Wells into the Mackenzie mountains, and Pangnirtung Pass) are major attractions.

The relationships between climate and the pursuit of various outdoor activities have been quantified to some degree for the Northwest Territories in general (Crowe, 1976) and for the Nahanni (Crowe *et al.*, 1979) and Auyuittuq (Masterton and Findlay, 1976) National Parks in particular. Aspects of concern are those of regional access, local access, and the activity itself (Table 6).

An analysis of climate in the Arctic, taking these various factors critical for recreation and tourism into account, resulted in an outdoor recreation-tourism climatic classification for the Arctic. Strong emphasis was placed on mobility as a key component of the viability of any activity; as a consequence, the classification was restricted to the summer and winter seasons since the short, transitional spring and fall periods posed substantial problems for mobility. The classifications are shown in Tables 7 and 8. Crowe (1976) presents bi-weekly maps of the areal extent of the various classes. A mid-winter (March 15) and mid-summer (August 15) map are included here (Figures 34 and 35) as examples.

Impact of Climate Change

Little work has been done on the impact of climate change on recreation and tourism in the Arctic. The importance of several combined climate factors in each season makes such analysis difficult, especially since visibility and wind are two of the factors and our understanding of expected changes in these climate variables is not great. Warmer temperatures would be expected to be beneficial for recreation and tourism in the Arctic (with, for example, the likelihood of extended summer activities into September, at least in the southwestern mainland areas). Yet their impact may be counteracted by stronger wind and/or reduced visibility in some areas, since increased precipitation is anticipated under a warming scenario (implying increased cloudiness and presumably decreased visibility). The visibility issue is particularly problematic since the current frequency of reduced visibility is greatly weighted by the occurrence of advection fog near decaying ice. With reduced ice in the future, a reduction in associated poor visibility events might result.

For the Mackenzie Basin Impact Study, two tourism studies were undertaken. One of these indicated that the effects of climate change might be detrimental to the Bathurst caribou herd (Brotton and Wall, 1997), important concerns being heavier snow cover and increases in the intensity and duration of insect harassment in the summer months resulting in caribou of very weak condition. Sport hunting could thus be hurt. The second study evaluated the implications of climate change for water-based activities in Nahanni National Park (Staple and Wall, 1996). One finding was the likelihood of only minor changes for river recreation such as canoeing and

Table 7. Winter recreation and tourism classification

Grade	Factor* Combinations	Capability for Recreation and Tourism
A	Ideal all factors	Excellent for non-residents and residents. No significant restrictions.
B	Two ideal, one marginal	Generally satisfactory for non-residents and residents. Length of daylight may be close to lower limits and wind-chill factor may approach lower limits for comfort and safety.
C	• Two ideal and one sub-marginal, or • One ideal and two marginal	Generally unsatisfactory for non-residents, but considerable activity possible by residents in local areas.
D	• One ideal, one marginal, and one sub-marginal, or • More than two marginal, or • More than one sub-marginal	Highly unsatisfactory for non-residents and extremely restrictive for residents.

* Winter climate factors are length of day, temperature, and wind.

from: Crowe (1976)

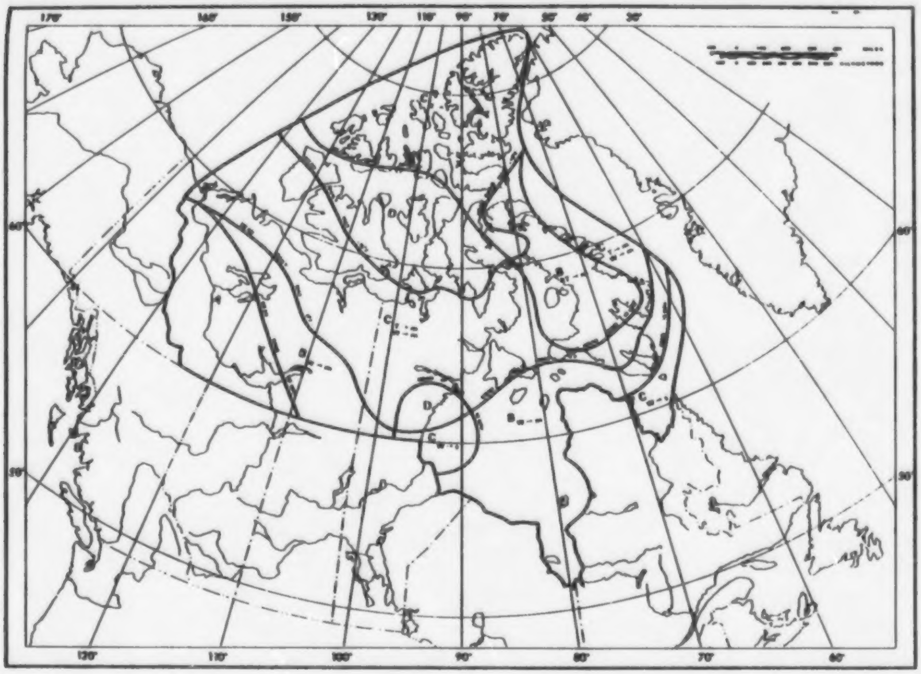
Table 8. Summer recreation-tourism classification

Grade	Factor* Combinations	Capability for Recreation and Tourism
A1	Ideal all factors	Excellent for non-residents and residents. No significant restrictions and most southern Canadian activities possible.
A2	Two ideal, one marginal	Generally good for non-residents and residents. Restrictions not particularly severe.
B	• Two ideal, one sub-marginal, or • One ideal, two marginal	Generally satisfactory for non-residents. Reasonably good for residents in local areas.
C	• One ideal, one marginal, and one sub-marginal, or • Three marginal	Generally unsatisfactory for non-residents. Generally satisfactory for residents in local areas.
D	Two marginal, one sub-marginal	Highly unsatisfactory for non-residents. Limited activity for residents.

* Summer climate factors are temperature, visibility, and wind.

from: Crowe (1976)

rafting due to changes in the hydrological regime of the area. On the other hand, forest fire and ecological changes traceable to climate change could have significant negative impacts. For example, photographic opportunities for particular wildlife and plant species may no longer exist within the park boundaries due to geographic shifts in ecological communities (although new species may be able to move in). Increased forest fire frequency would threaten the execution and enjoyment of hiking and landscape viewing, and if severe enough would cause park closings, thus counterbalancing any longer season due to higher temperatures.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60°
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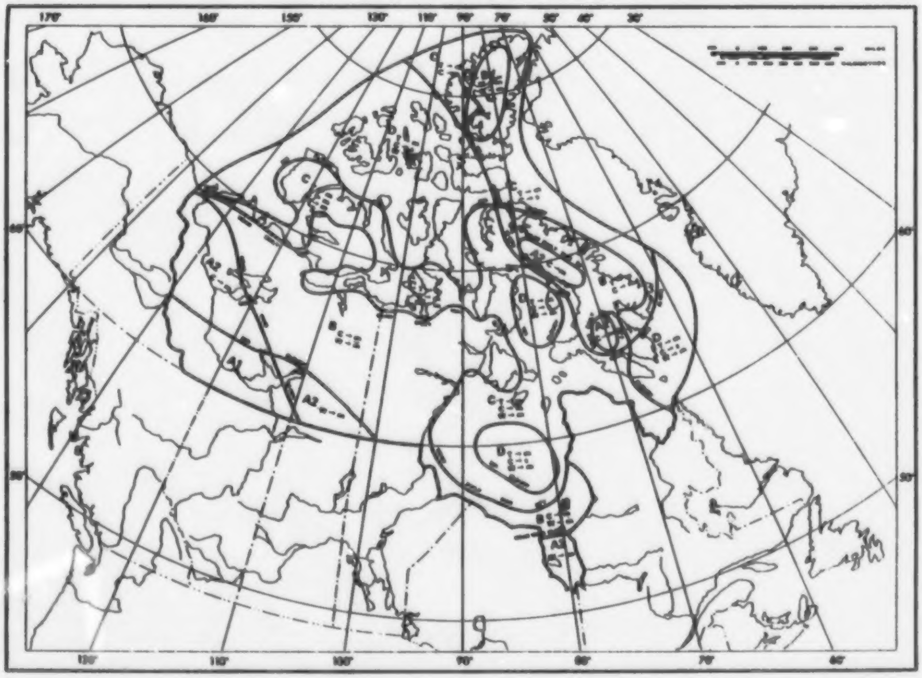
C
D

Figure 34. Winter recreation and tourism classification (from Crowe, 1976)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A1
A2
B
C
D

Figure 35. Summer recreation and tourism classification (from Crowe, 1976)

Settlements, Country Food and Human Health

The Mackenzie Basin Impact Study devoted significant efforts to addressing the impacts of climate change on communities in the Mackenzie region, but the issue is complex and much research is still needed (Cohen, 1997b). Community response to the impacts of climate change will be influenced by economic, technological, political, and social change, just as the impacts of present-day climate are so influenced. For example, current responses to flooding in northern Mackenzie Valley vary depending on previous community experience, availability of all-season roads, and arrangements with other levels of government (Newton, 1997). Under climate change, floods would still occur, but there would be problems associated with lower minimum water levels (Kerr, 1997). Landslides and ground subsidence due to permafrost thaw would present increased risk to some communities (Bone *et al.*, 1997).

Many Arctic communities are predominantly populated by aboriginal peoples. In such settlements, the subsistence sector (reliance on country food) may be worth about $15,000 per household annually and is often one-quarter to one-half of the total local economy. The long-term evolution of these wage and non-wage economies will be influenced by land claims and various external economic pressures (Lonergan and Kavanaugh, 1997). Climate change, however, will also be an important determinant. It will affect the distribution of wildlife and other resources upon which the northern non-wage economy is based. At the same time, traditional knowledge and local adaptations currently used may no longer be applicable enough to rely on. Associated with climate change too may be effects on the health of northerners through dietary dislocations and epidemiological changes (Fast and Berkes, 1998).

The successful pursuit of country food whether by hunters, trappers or fishers is very greatly influenced by factors such as wildlife distributions and behaviour, and climate patterns (which govern such things as snowfall amount, snow cover patterns, precipitation type, extended periods of hot or cold temperature, freeze-thaw cycles, timing of break-up and freeze-up on lakes, rivers, and marine areas - all indicators affecting wildlife and vegetation). The reliance on country food by generations of aboriginal peoples has built up a cultural store of knowledge and beliefs about the land which guides country food pursuit. This is sometimes referred to by western scientists as traditional ecological knowledge (TEK). An example of the range of information available from this knowledge base for the Hudson Bay-James Bay area is shown in Table 9. Although it is clear from this that TEK can be of great value in contributing to understanding of environmental change (Fenge, 1996), in recent years, there have been instances where such knowledge has been severely tested by climate conditions which are outside historical remembrance. Future climate change is likely to test the applicability of such knowledge even further.

Since the 1950s and 1960s when many northern aboriginal peoples were settled into year-round villages, the decline in the proportion of aboriginal peoples' diet provided by hunting and fishing has resulted in dietary problems and medical costs through elevated levels of cardiovascular disease, diabetes, and vitamin-deficiency disorders. This has come about through less physical activity; less fresh meat and more fat, sugar and processed foods; a higher birth rate; and changes in social and cultural values. In addition, the safety of the country foods that are eaten has been raised as a major concern at community meetings in such locations as Iqaluit (Canadian Polar Commission, 1996), Pond Inlet, Arctic Bay, Repulse Bay, Gjoa Haven and Coral Harbour. The safety factor arises from the increased contaminant levels found in country foods, the main mechanism for which is the long-range atmospheric transport of pollutants to the Arctic from industrialized areas to the south. PCBs and other organic contaminants occur at concentration levels of concern particularly in the large marine mammals. (Some Inuit women in the Hudson Bay area are known to have PCB concentrations in breast milk which are 5 times higher than in that of southern Canadian women.) Among the heavy metals, cadmium and lead can be a problem (Fast and Berkes, 1998). Such contamination problems have interfered with country food harvesting since the mid-1970s. Future climate change is likely to provide further interference to such harvesting through altered

Table 9. Environmental changes in the Hudson Bay bioregion observed by Cree and Inuit

	Eastern James Bay	Eastern Hudson Bay	Hudson Strait	Northwestern Hudson Bay	Western Hudson Bay	Western James Bay
Weather	• colder winters in reservoir areas • shorter fall and spring seasons • greater variability in fall • increased snowfall	• persistence of cold weather into spring • snow melts later • spring & summer cooling trend • less rain; fewer thunderstorms	• greater variability; less predictable • cooling trend • new snowfall cycle • longer winters; snow melts later • less rainfall	• greater variability • warmer and shorter winters • snow falls and melts earlier • cool summers in early 1990s	• longer winters • colder springs • snow melts faster	• shorter and warmer winters • spring wind shifts several times a day
Sea ice	• salinity changing along NE coast • more freshwater forming in the Bay • less solid in La Grande River area; freezes later, breaks earlier	• freezes faster • solid ice cover is larger and thicker • fewer polynyas • floe edge melts before breaking up	• freezes faster • poor quality • landfast ice extends further offshore • polynyas freeze • floe edge melts before breaking up			
Currents	• weaker in Eastmain area • swifter and less predictable north of La Grande River	• weakening currents	• weakening currents	• weaker currents in Roes Welcome Sound		
Rivers	• seasonal reversal in levels and flow • decline in water quality • unstable ice on La Grande R.; freezes later, breaks earlier • vegetation dying along diverted rivers	• decreased water levels and river flow	• decreased water levels and river flow	• decreased water levels and river flow	• seasonal reversal in water levels and flow • increased salinity, erosion and sediment in Nelson River • decline in water quality	• decreased water levels and river flow in southern James Bay rivers • increased erosion and mud slides
Atmosphere	• change in sky colour	• change in sky colour • sun's heat blocked by haze	• change in sky colour • sun's heat blocked by haze	• change in sky colour	• change in sky colour	• change in sky colour
Canada geese and snow geese	• coastal and inland habitat changes • coastal flyways have shifted east • fewer being harvested in spring and fall • large flocks of non-nesting/moulting geese along coastal flyway	• smaller flocks of Canada geese arrive in Belcher Islands since 1984 • increase in non-nesting/moulting geese in Belcher Islands and Long Island	• new snow goose migration routes • increase in number of moulting snow geese • Canada geese no longer nest in Soper River area	• more Canada geese in Repulse Bay area during summers of 1992 and 1993	• more snow geese migrating to and from the west • habitat changes at Marsh Point staging area • earlier and shorter fall migration	• habitat changes in Moose Factory area • more snow geese flying in from the west • Canada geese arrive from the north first part of June • change in fauna migration patterns
Beluga	• decrease in numbers	• decrease in numbers				
Polar Bear		• increase in numbers		• increase in numbers • appear leaner and more aggressive		
Walrus		• shift away from Sleeper and Belcher Islands	• increase in numbers around Nottingham Island	• decrease in numbers near Arviat and Whale Cove • increase in numbers near Coral Harbour and Chesterfield Inlet	• decrease in numbers around Attawapiskat	
Fish	• mercury contamination • loss of adequate habitat for several species, e.g., whitefish, sturgeon, pike, etc.	• decrease in Arctic char and Arctic cod in Inukjuak area		• cod are no longer found near shores off Cape Smith and Repulse Bay		
Moose	• sharp decrease is numbers				• change in the taste of the meat	
Caribou		• change in diet • very large herds • travelling closer to coast	• increase in abnormal livers, i.e., spots and lumps	• sharp increase in numbers • crossing to islands • change in diet	• migration route has shifted inland	

from: Fenge (1996)

contaminant pathways and consequently, exacerbation of dietary dislocations.

Agriculture and Forestry

The agriculture and forestry industries (along with fisheries) are very modest contributors to the GDP of the Arctic. In 1993, agriculture and related services represented about 0.06% of GDP while forestry represented 0.1%.

Agriculture

Background and Sensitivity to Climate

There are a number of factors which determine the agricultural capability of land. These include soil type, landscape characteristics (slope, stone content and flooding capacity) and climate. Climate will affect the overall capability rating only if the other two factors are not limiting (Brklacich and Tarnocai, 1990).

In Arctic Canada, soil type and landscape characteristics pose major constraints to agriculture. The Nunavut area which is all part of the Canadian Shield is characterized by soils which are either very stony with rocky outcrops on Baffin Island, the central High Arctic islands, and on the eastern mainland, or alluvial (often poorly drained) on Ellesmere, Devon and Axel Heiberg Islands and on the extreme western Arctic islands. In the western Arctic (Mackenzie Valley area), soils range from poorly drained alluvial in the Delta, to bog and sub-Arctic (with large areas away from the Valley very stony) in the central-to-lower part of the Valley, to gray-brown (dry in summer) forest soils in the central-to-upper area to the west of Great Slave Lake. On this basis, in the Arctic Region, only areas in parts of the Mackenzie Valley extending from about Norman Wells southward to the Alberta and British Columbia borders (along the Liard Valley) currently offer potential for agricultural practice.

The climate factor is mainly concerned with air temperature as indicated by the length of the frost-free period and the heat accumulation during the growing season (growing degree-days above 5°C), and moisture supply (May-through-September difference between accumulated precipitation and potential evapotranspiration). In the lower Mackenzie Valley, a short, cool frost-free period of 62 days imposes extremely severe limitations for agricultural production and opportunities would be confined to native range. On an agricultural potential scale of 1 to 7 (class 1 = no significant limitations to agriculture, class 7 = no capability for agriculture), the area would be in class 6. In the central Mackenzie Valley, the frost-free period is about 95 days but still cooler (average 14.4°C) than the temperature requirement for most field crops. The central Mackenzie Valley would be in class 5. In the upper Mackenzie Valley, the frost-free period and its average temperature are 10% longer and 0.5°C warmer respectively than in the central area - improvements, but still imposing severe limitations to agriculture (class 4) (Brklacich and Tarnocai, 1990). Moisture deficit characteristics impose lesser constraints on agriculture in the two more northerly areas, but temperature is the limiting climate factor.

Adaptation to Current Climate

In Canada as a whole, adaptation of agriculture to current climate is an issue of some debate (Smit, 1993), with there being opposing views that agriculture is or is not well adapted. For Arctic Canada, the relative dearth of commercial agricultural potential has meant that there has been little successful adaptation to date.

Impacts of Climate Change

Climate change scenarios used by Brklacich and Tarnocai (1990) and Brklacich *et al.* (1997) relax the constraints imposed upon agricultural capability (spring-seeded cereal crops) by current climate conditions. This would not be sufficient to support commercial agriculture in the lower Mackenzie Valley, but would offer opportunities in the central and upper Mackenzie Valley areas. For example, wheat production could improve but expanded irrigation services would be needed. Potential increases in wheat yield from elevated CO_2 levels would be offset by shorter grain filling time and less favourable soil moisture (Brklacich *et al.*, 1997).

Adaptation to Climate Change

- Use of longer spring season wheat cultivar would provide only minor improvement.

- Winter wheat cultivar may provide improved yields in the south.
- Expanded irrigation would overcome projected deficits in soil moisture.

Forestry

The timber-producing land in the Arctic is found in the upper Mackenzie Valley area extending from Hay River to the Liard River and along the Mackenzie River downstream to Norman Wells. Some 10 to 15 million hectares are involved, most of which is under territorial ownership. About one-third of this is mature timber.

The impact of climate change on the forest industry has not been rigorously looked at for the Arctic. The Mackenzie Basin Impact Study did address forestry, but the geographic focus was on the portions of British Columbia and Alberta within the Basin (Rothman and Herbert, 1997). The results for northeastern BC and northern Alberta, however, provide some indication of potential impacts within the adjacent Arctic region. The direct impacts of a warmer climate would be an increase in mortality for softwoods but improved growth for hardwoods. Increased forest fire frequency and severity, however, would also occur, resulting in decreased average tree age in general. As a consequence, the yield from all stands of commercial timber, both softwoods and hardwoods, would decline by 50%. Expansion of the range of forest pests such as the white pine weevil would cause additional stress (Hartley and Marshall, 1997; Kadonaga, 1997; Sieben *et al.*, 1997).

Fisheries

The fisheries industry in the Arctic comprises commercial, recreational, and subsistence fisheries. These are primarily freshwater in nature. Of these three, subsistence fishery is particularly important in the Arctic, with a recent estimate (Clarke, 1993) suggesting about 12,000 subsistence fishers whose activity had a gross value of $15 million in 1987.

Shuter *et al.* (1998) have looked at climate change impacts on fisheries across Canada and drawn several conclusions for the Arctic. For both marine and freshwater areas, an increased overall sustainable harvest is foreseen due to anticipated increases in overall fish production. This is related to a longer, warmer growing season and less ice cover which will mean more intense nutrient recirculation from wind-generated turbulence and higher fish species diversity and individual species populations. The location of preferred fishing areas and fish catchability will alter both temporally and spatially, in accordance with changes in the location of ice edges and polynyas. There is potential for the establishment of self-sustaining pacific salmon populations, particularly sockeye, in the western Arctic. Emphasis on adaptation at the local level has been urged for the fishery industry across Canada. This will be particularly important in the Arctic, with the significant subsistence component of its fisheries activity.

Defence

Since the 19th century, the history of the Arctic has been characterized by military ventures, initially aimed at exploration but later at development and defence. Over the past half century, the involvement has included such activities as aerial photographic surveying; operation of the Distant Early Warning (DEW) line; establishment of weather stations and navigational aid networks; research into clothing and mobility; aerial, land and naval patrols in support of sovereignty; search and rescue; and construction of related infrastructure in many instances.

As a consequence of this wide range of activities, all aspects of Arctic climate have at one time or another been of interest to the military. Air temperature, cloud and visibility, snow cover, sea-ice characteristics, and permafrost are major elements of concern and have involved military investment in research.

Historical Adaptation

As the exploration period of the 1800s progressed, Inuit clothing styles were increasingly adopted by naval personnel as was the practice of walking in pairs so that one could warn the other about frostbite. In the 20th century, reliable native technologies such as travel by komatiks and dog teams were taken advantage of for land operations as were native guides when entering unknown territory (Smit, 1993).

Impact of Climate Change

Some specific concerns for military operations as outlined by Cowan (1990) include:

- Icebergs will not only provide a hazard to navigation, but sea-bed scouring by icebergs will be a hazard to permanent arrays of hydrophones.
- An increase in cloud cover and fog will affect air and sea operations. Surveillance and search and rescue operations would also be limited.
- Increased snow would affect surface transportation. This could alter Arctic concepts for land-based winter operations. Similarly, land summer operations including construction would be affected by decreased permafrost (see also Tucker and Judge, 1991).
- The reduction of Arctic sea ice could change the salinity structure of the sea altering the propagation of sound which will affect the performance of sensors used for underwater detection. The ambient noise characteristics of the sea will change.

Generally, Canada's position that all waters within the Archipelago are under its sovereign control could be more seriously tested due to more easy access. Increased surveillance and other activities, such as a greater search and rescue capability, will be required. The lower probability of extremely cold weather would result in Arctic weather and climate being looked upon by strategists as less of a natural defence in its own right. Military sites such as Alert will face altered costs due to changes in space heating requirements and infrastructure maintenance. Overall, an increased DND role with attendant costs is envisaged.

Adaptation to Climate Change

- Increased aviation meteorological services and improved marine forecasting speed and accuracy may involve new technologies and expanded coverage of observations.
- Canada's current position on its sovereignty over internal Arctic waters is partially related to their ice-covered nature. As this changes, Canada may have to adapt its sovereignty position or definition accordingly (Smit, 1993).

E. OPPORTUNITIES FOR FURTHER RESEARCH

Impacts

For some time, it has been acknowledged that the Arctic will be a region of the Earth in which the impacts of future climate change will be felt earliest and most keenly. As a result, over the past ten years there has been considerable attention given to trying to quantify those impacts through research activities carried out both within Canada and without. The resulting volume of literature is substantial and touches many aspects of the biophysical environment as well as socio-economic activities. In addition to work dealing with these aspects individually, the literature includes the results of the Mackenzie Basin Impact Study - a regional climate impact study focussing on part of the Arctic and one of the first such studies done anywhere in the world (Cohen, 1994a). (Regional climate impact studies are evaluations aimed at integrating various impacts in order to get a picture of what climate change might mean to the life and economy of a region as a whole.)

Despite the work to date, however, there are still many gaps and uncertainties in our understanding of climate impacts for the Arctic. (Some sectors, such as finance and insurance, have not been looked at for the Arctic at all.) The concerns can be classified as both small scale and/or specific as well as large-scale and/or general, for want of a better way of differentiating them.

Small scale and/or specific

A number of conferences, workshops, and state-of-the-art reports during this decade have identified research needs and priorities for various aspects of the physical and biological environments of the Arctic as well as socio-economic activities. Many of these deal specifically with either sensitivities to climate or the impacts of climate change. Table 10 lists some of the more recent sources.

Large scale and/or general

- Environmental monitoring: Commitment to continued monitoring of atmospheric and oceanographic variables throughout the Arctic is needed in order to follow trends, provide input to models, and improve understanding of the relationships between climate and other environmental and socio-economic information.
- Climate scenarios: There is a need for more credible and detailed regional scenarios than currently available from the GCMs. Work with Arctic regional climate models to date suggests that further efforts of that nature would be useful.
- Geographic emphasis: The eastern Arctic is much less well-studied in terms of impacts than the other regions of the Arctic. This is a significant gap in view of the cooling occurring there compared to general warming occurring elsewhere in the Arctic.
- Socio-economic sectors: While there are significant gaps in our understanding of the sensitivities to climate of all aspects of the Arctic physical, terrestrial, and aquatic environments as well as the potential impacts on them due to climate change, even less well studied are the existing and potential relationships between climate and socio-economic sectors in the Arctic.
- Traditional ecological knowledge: TEK has much to offer, particularly in respect to quantifying terrestrial and aquatic environmental sensitivity to climate. The continuing applicability of such knowledge in the face of changing climate, however, is being pressured. Further research into how TEK can be most effectively tapped and utilized is needed.
- Stakeholders: Research in the area of climate change impacts and adaptation should involve both users and researchers working together in all phases: planning, development and implementation. It is the users in the region who have experienced and reacted to climate historically, and it is they who will have to adapt in the future. They have the best knowledge of where lack of understanding exists and what needs are most important, and that should be capitalized on in developing research programs.

Adaptation

A wide range of adaptation has historically characterized activities in the Arctic. Much of this has

Table 10. Sources of recommendations for impact research on specific socio-economic sectors and aspects of the biophysical environment

Topic	Sources of recommendations
Hydrology	Prowse and Ommanney (1990), IPCC (1995), ACSYS (1996), Rouse *et al.* (1997)
Permafrost	IPCC (1995), EARG (1997)
Sea Ice	IPCC (1995), ACSYS (1996)
Glaciers and Icebergs	IPCC (1995), Jania and Hagen (1996),
Sea Level, Ocean Circulation and Coastal Processes	IPCC (1995), ACSYS (1996)
Terrestrial Ecosystems	IASC (1994), Oechel and Holten (1994), IPCC (1995)
Marine Ecosystems	IASC (1994), IPCC (1995)
Socio-Economic Sectors	Wall (1993), IASC (1994), IPCC (1995), Canadian Polar Commission (1996), Cohen (1996a, 1997b), Everett *et al.* (1997), Canada Country Study (1998a, 1998b)

occurred in an ad hoc fashion and should be better documented, as there are valuable lessons to be learned. Neither the application of such adaptive responses to nor the development of possible new adaptive measures for dealing with future climate change have been investigated rigorously for the Arctic; however, some expert opinion has been offered (Nuttle, 1993 - water resources; Smit, 1993 - oil and gas, defence; Woo *et al.*, 1993 - permafrost; LeDrew and Barber, 1994 - marine cryosphere; Proctor, 1995 - marine; Canada Country Study, 1998a - socio-economic sectors including agriculture, built environment, energy, fisheries, transportation, etc.; Canada Country Study, 1998b - cross-cutting issues). The whole adaptation area is wide open for future research.

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